Boeing Research & Technology

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Trailblazing

Applications of Flow Control to a Commercial Aircraft

In Memory of John Lin

Arvin Shmilovich[1], Paul Vijgen[2]

[1] Boeing Research and Technology

[2] Boeing Commercial Aircraft (Retired)

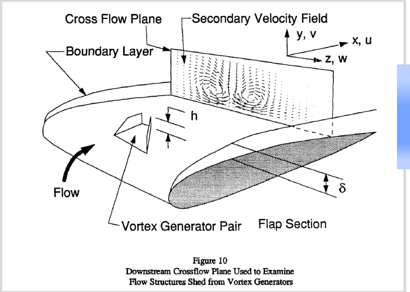
Advanced Modeling & Simulation (AMS) Seminar Series

NASA Ames Research Center, May 25th, 2023

Producing
Leading
Creating
Researching
Analyzing

In Memory of John Lin
1957 - 2021

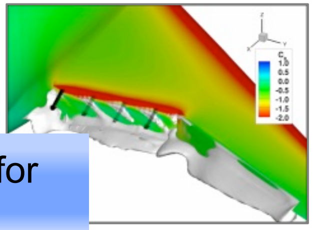
A prolific researcher at NASA Langley, and a great colleague and friend

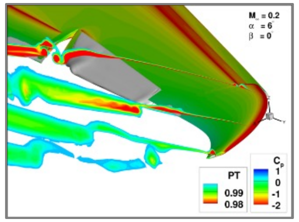


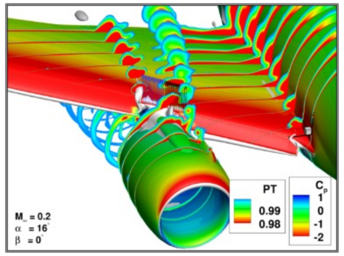
Passive Flow Control with Micro Vortex Generators

Full-Scale Active Flow Control Enhanced Vertical Tail

High-Lift
Common Research Model





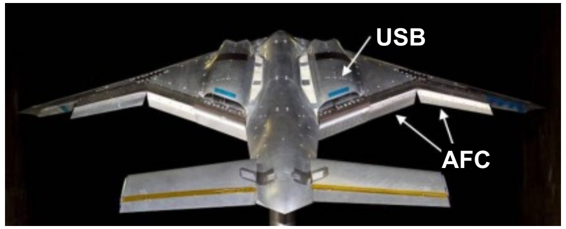


Active Flow Control for High-Lift

NASA/Boeing AFC Collaborations

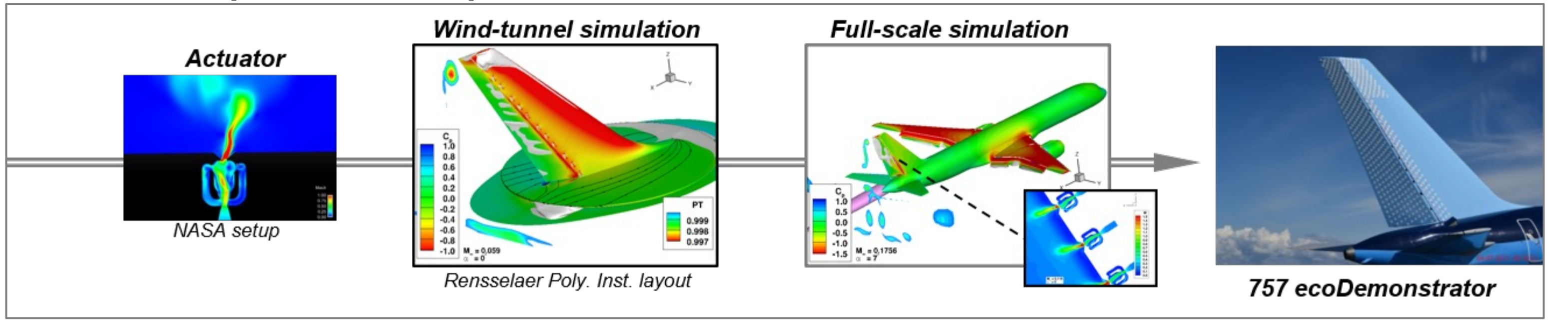
- **ATT (2002)**
  - Prop STOL
  - With AFRL

- **AJACS (2012)**
  - STOL USB/AFC
  - With AFRL



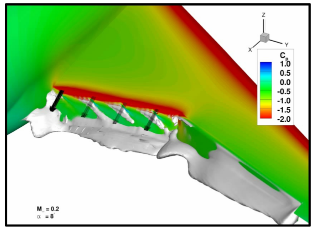
AIAA 2013-1097
AIAA 2013-2796

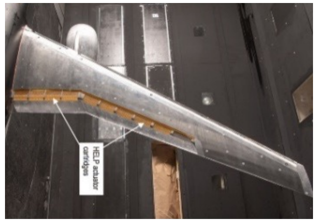
- **Boeing 757 ecoDemonstrator (2012-2015)**
  - Vertical tail



AIAA J, Vol. 56, No. 9, 2018
AIAA J, Vol. 56, No. 12, 2018

- **CRM/AFC (2016)**
  - Simple hinge flap





AIAA 2017-0321
AIAA 2017-0322

- **Localized AFC (2020)**
  - Small modification, high payoff

AFC Active Flow Control
ATT Advanced Theater Transport
AJACS Advanced Joint Air Combat System
STOL Short Takeoff and Landing
USB Upper Surface Blowing
CRM Common Research Model

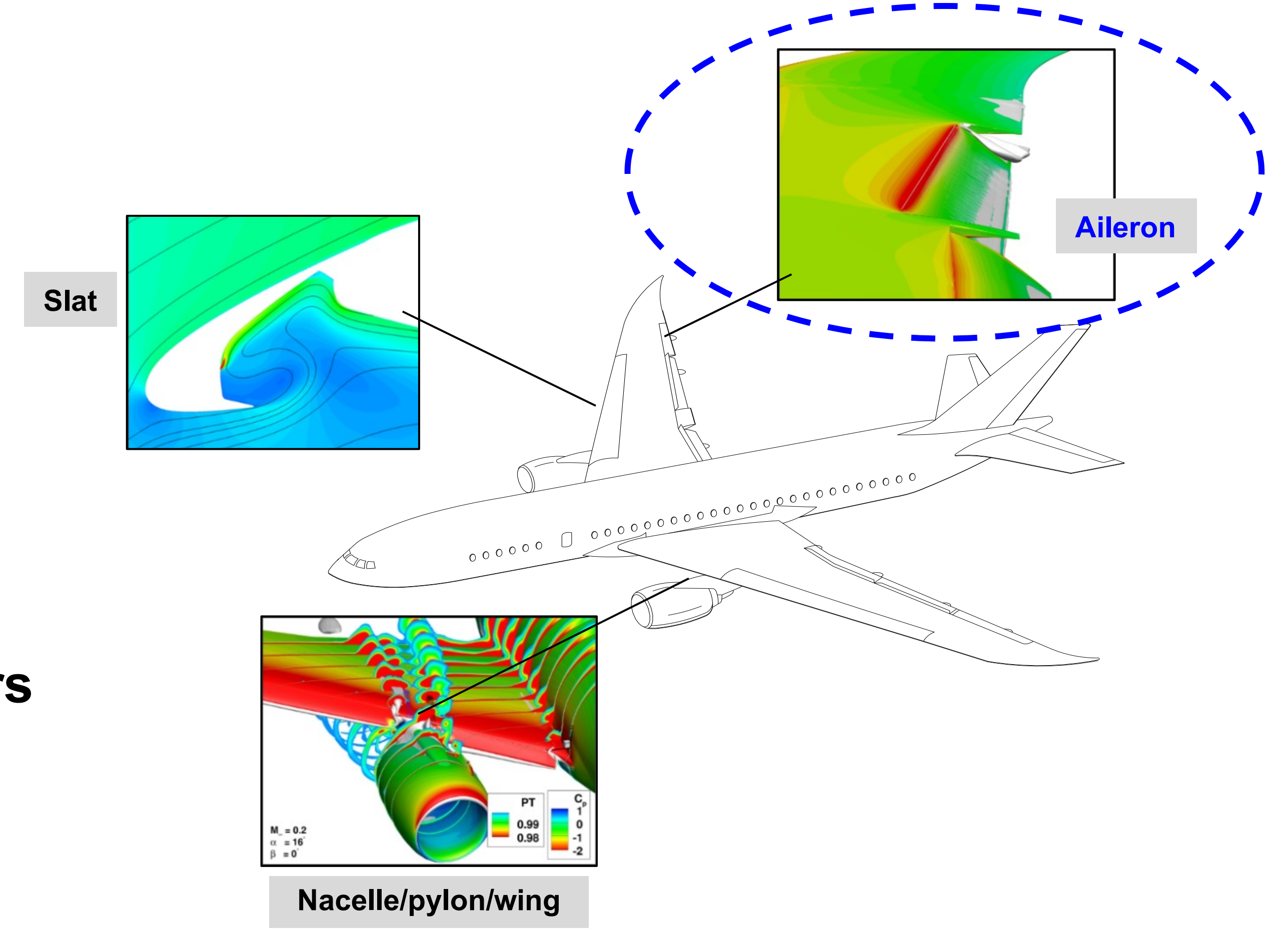
Motivation

- **Improve airplane performance by increasing L/D, C_L, $C_{L,max}$ during high-lift**
  - **Higher payload, longer range, shorter runway** (AIAA 1991-1527)
    - Δ(L/D) = +1% in takeoff is equivalent to a 2,800lbs increase in payload or a 150nm increase in range
    - A 1.5% increase in $C_{L,max}$ is equivalent to a 6,600lbs increase in payload for a fixed approach speed

- **Localized AFC concepts**
  - **Aileron**
  - **Wing Leading Edge**
    - Slat
    - Nacelle/pylon/wing

- **NASA/Boeing collaboration**
  - **NASA PMs – John Lin, Latunia Melton**
  - **Boeing PM – Rene Woszidlo**

- **Study described in three SciTech 2023 papers**
  1. **Aileron** AIAA 2023-0655
  2. **Wing LEs** AIAA 2023-0656
  3. **System Integration** AIAA 2023-0657



AFC = Active Flow Control

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Flow Control for Enhanced Aileron Effectiveness on a Commercial Aircraft

Arvin Shmilovich[1], Yoram Yadlin[1], Paul Vijgen[2], Rene Woszidlo[1]
[1] Boeing Research and Technology
[2] Boeing Commercial Aircraft (Retired)

AIAA SCITECH 2023
AIAA-2023-0655
Session: APA-24, Flow Control Applications
Including Experiment and Computation IV
Tuesday Jan 24, 2023

Producing
Leading
Creating
Researching
Analyzing

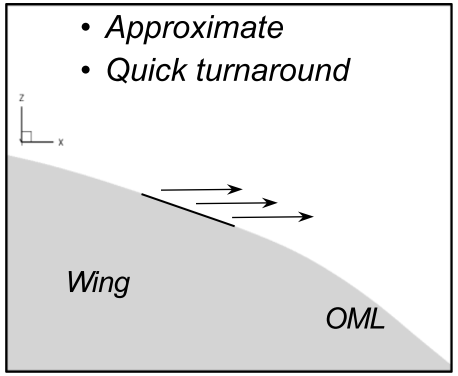
Numerical Procedure

OVERFLOW

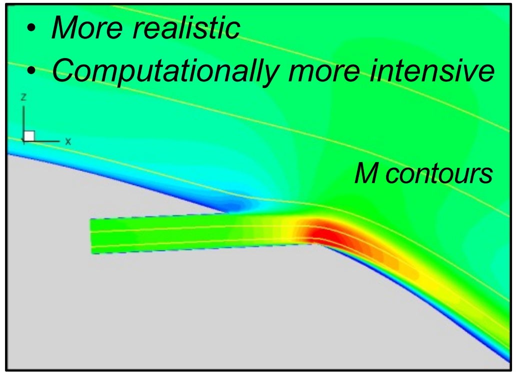
– Overset grid system
– Special boundary conditions for various actuation techniques introduced by Boeing[1-3]
– Accuracy[4]
  • Upwind differencing, *O*(2)
  • Time-stepping scheme, *O*(2)
– Method validated for various AFC applications[5,6]

AFC modeling

– Steady actuation (has practical advantages[7])
  • Surface Boundary Conditions (BCs)
  • Convergent/divergent (CD) nozzle
  • Discrete CD ducts



Surface BCs



Embedded CD actuators

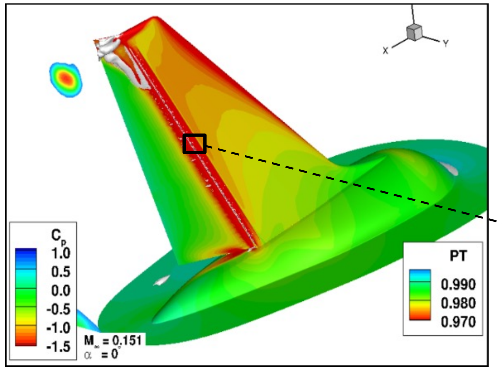
1 AIAA J., Vol. 49, No 3, 2011
2 AIAA 2016-3309
3 Notes on Num. Fluid Mech., Springer, Vol. 145, 2020
4 AIAA J., Vol. 54, No. 8, 2016
5 J. of Aircraft, Vol. 45, No. 5, 2008
6 AIAA J., Vol. 57, No 1, 2019
7 AIAA 2023-43101

CD = convergent/divergent

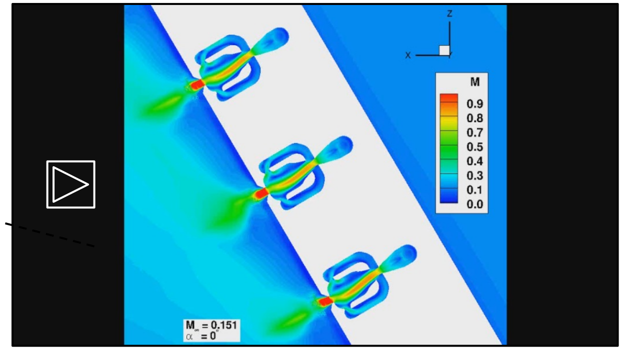
CFD Validation vs. NFAC Wind-Tunnel and Flight-Test – AFC-On

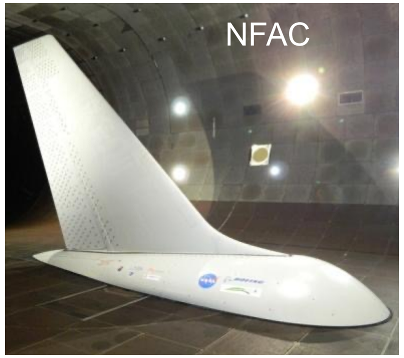
- **Experiment - FOs on the vertical tail**
  - NASA Ames NFAC
  - Flight test Boeing 757 ecoDemonstrator[1]
- **CFD - OVERFLOW**[2]
  - Unsteady actuation

NFAC

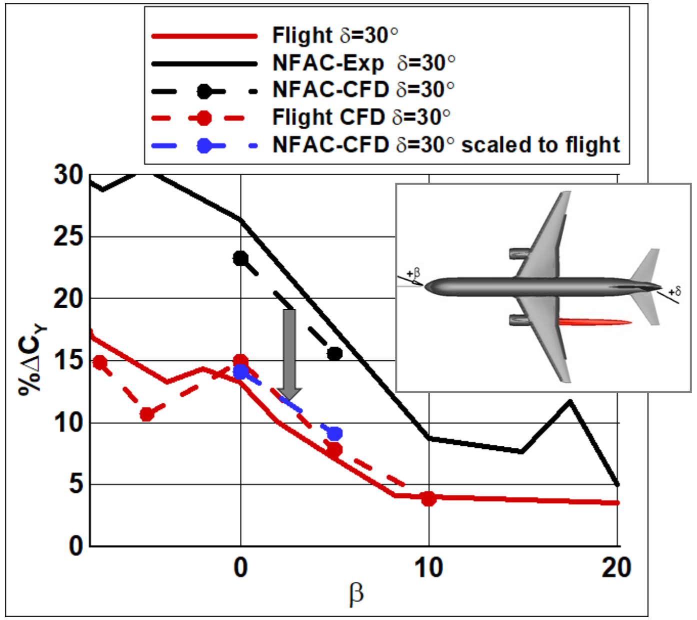


FOs

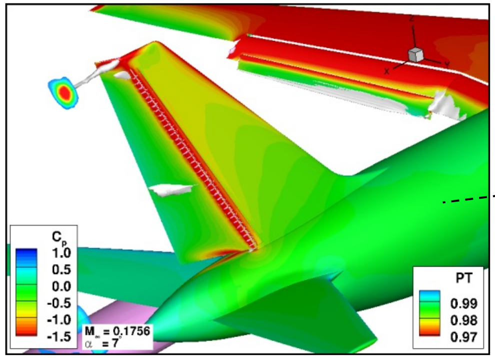




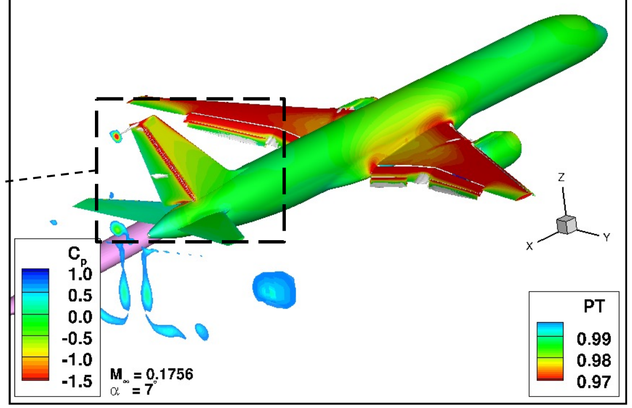
Side force vs. airplane yaw angle



Flight



One Engine Inoperative flight condition



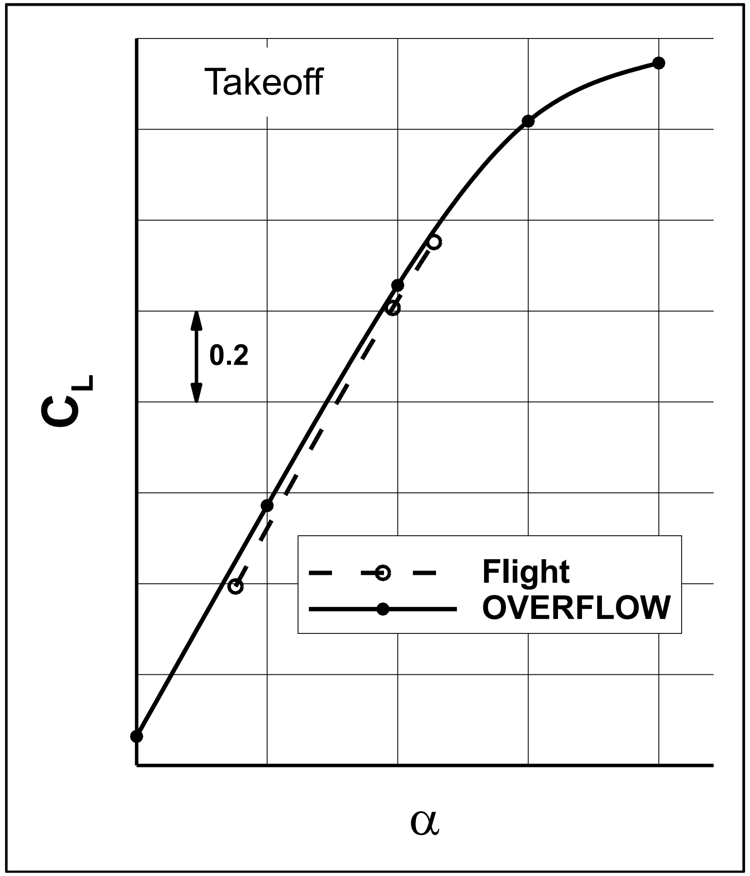
Acceptable agreement given the uncertainties in flight data

1 AIAA J, Vol. 56, No. 9, 2018
2 AIAA J, Vol. 56, No. 12, 2018

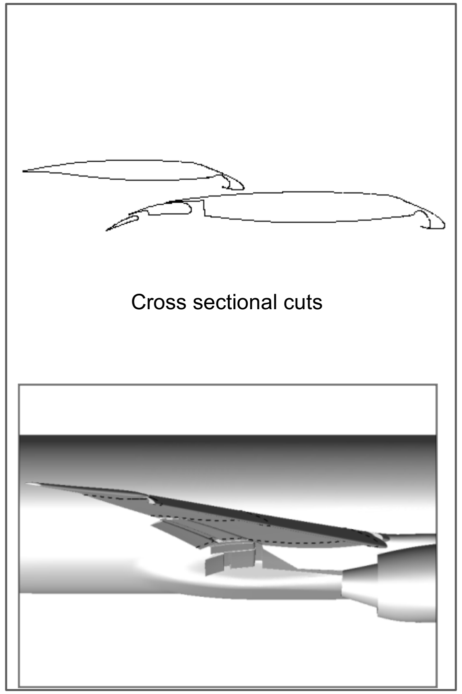
FO = Fluidic Oscillator
NFAC = National Full-Scale Aerodynamics Complex

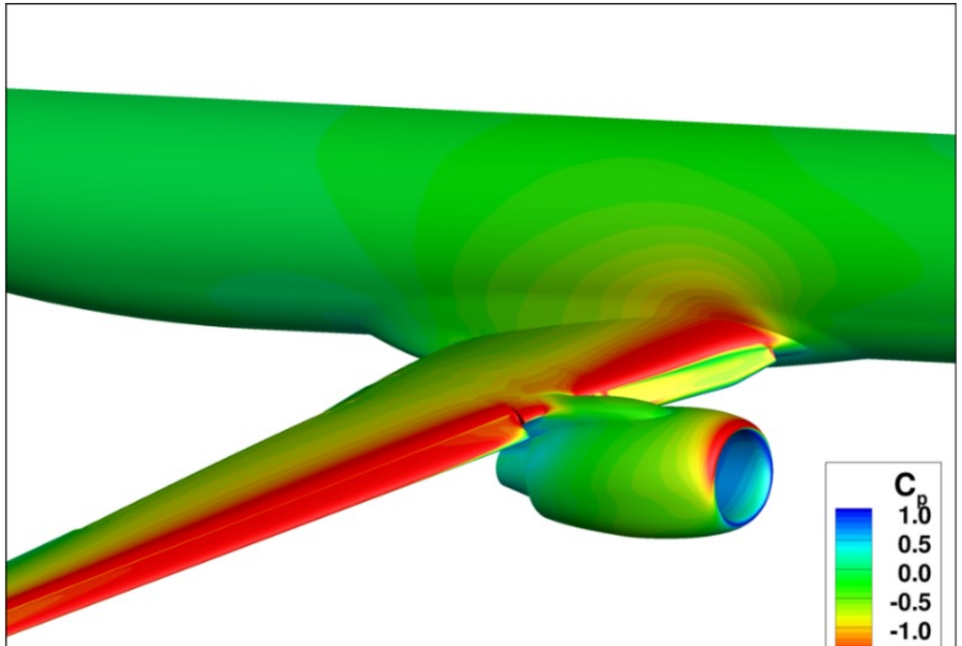
CFD Validation vs. Flight Data – AFC-Off

- **No experimental data is available for the AFC applications considered in this study**
- **Limited validation for a similar baseline configuration**



Good agreement for high-lift configuration

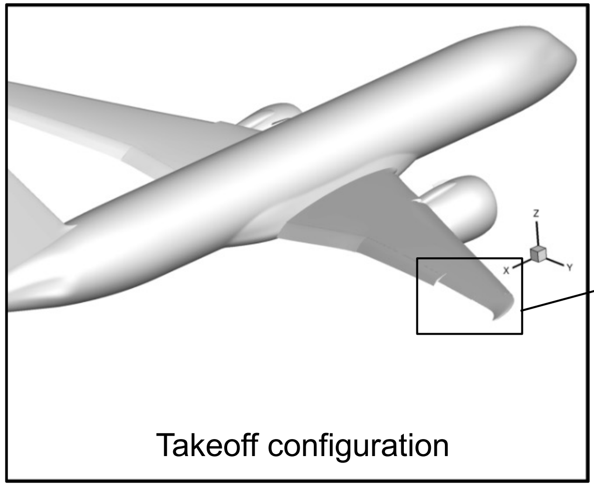


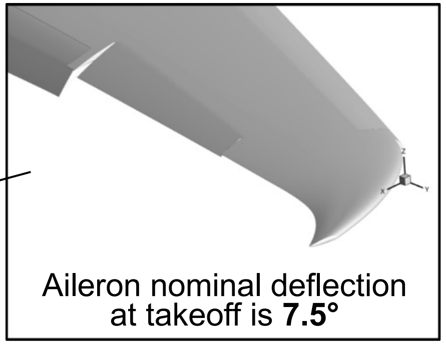


Geometry used in [AIAA 2020-0784]

Reference Aircraft and Grid Setup

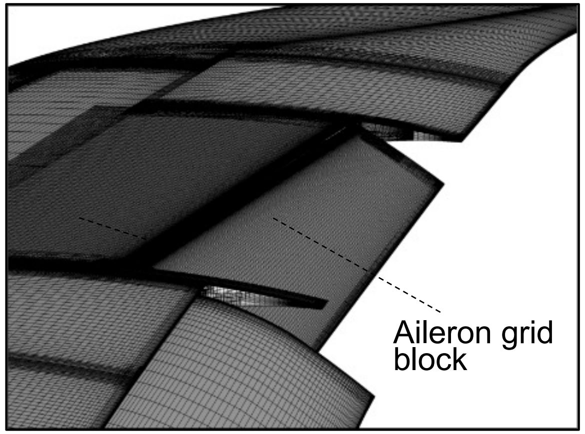
- **Notional short/medium-range twin-engine airplane**
  - Relevant to future platforms
  - High-lift system – Krueger/slats, single-slotted flap
  - Takeoff flap setting



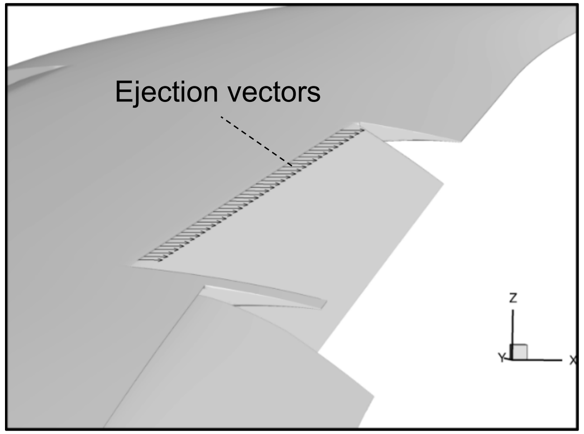


- **Objective – Higher aileron deflection + AFC**
  - Increase L/D, C_L, $C_{L,max}$

- **Initial CFD setup for AFC**
  - Aileron deflected to **25°**
  - AFC
    - Surface BCs (initially)
    - Applied on a strip of constant width along the hinge line
    - Jet angle is specified
    - AFC intensity is determined by PR, TR
  - Flow conditions
    - M=0.20
    - Re = $6 \cdot 10^6$
    - Fully turbulent (SA turbulence model)



~70 million grid points



AFC applied at the hingeline

PR, TR = pressure, temperature ratios

Aileron Deflections (Baseline, AFC Off)

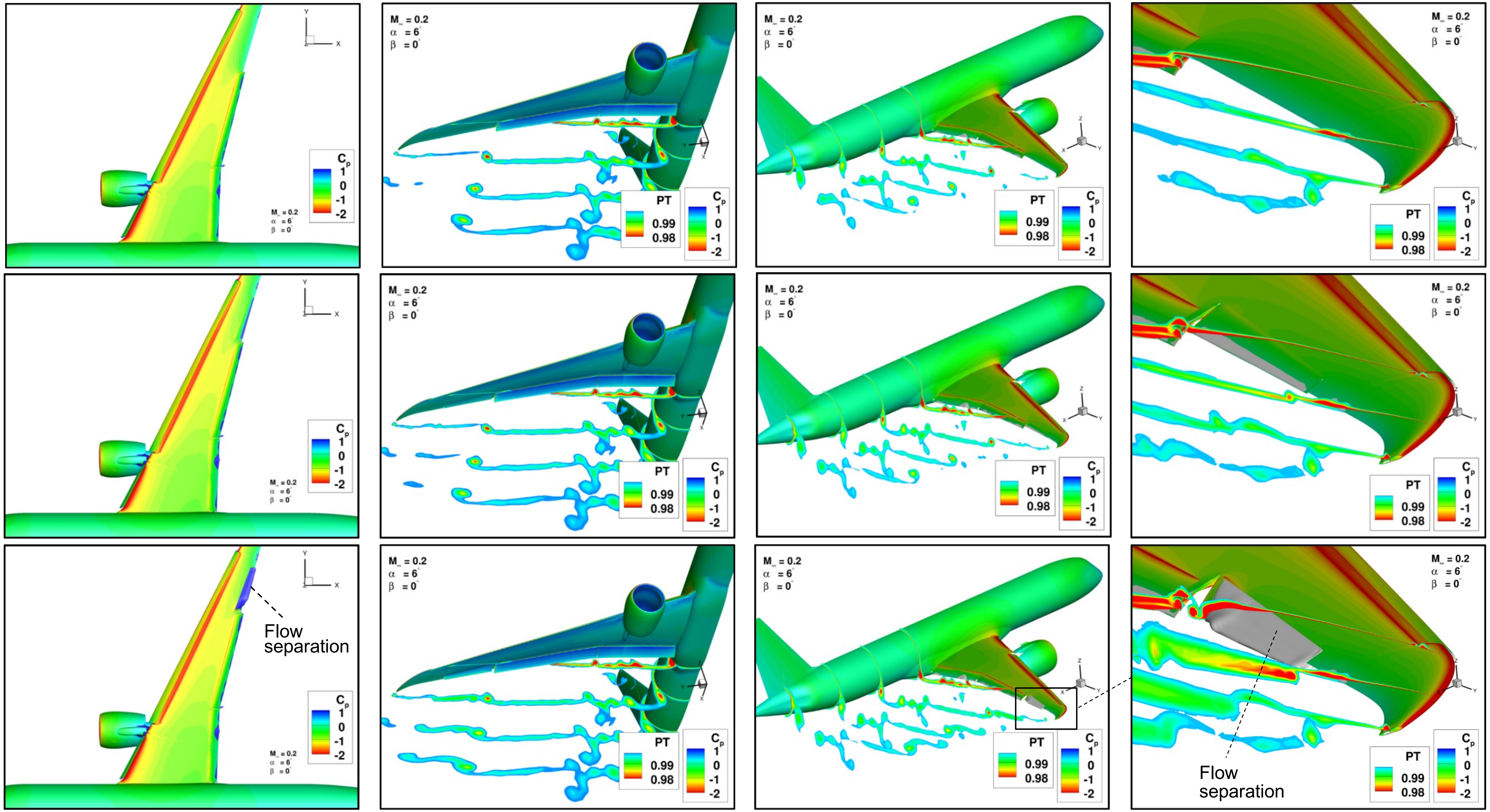
Cp = Pressure coefficient on surfaces
PT = Normalized total pressure on wake cuts

Nominal takeoff, α=6°

Ail 0°

Ail 7.5° (nominal)

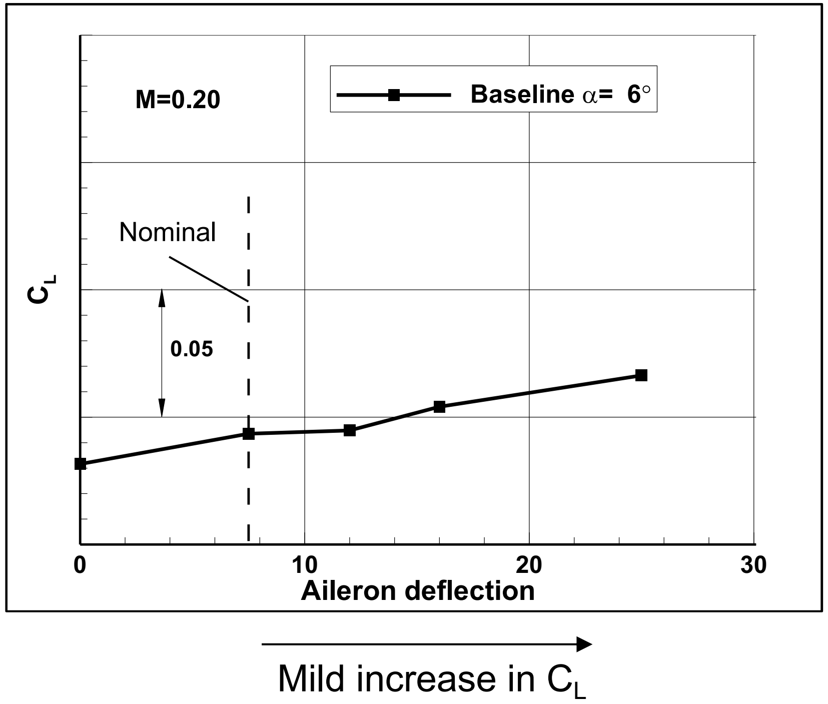
Ail 25°

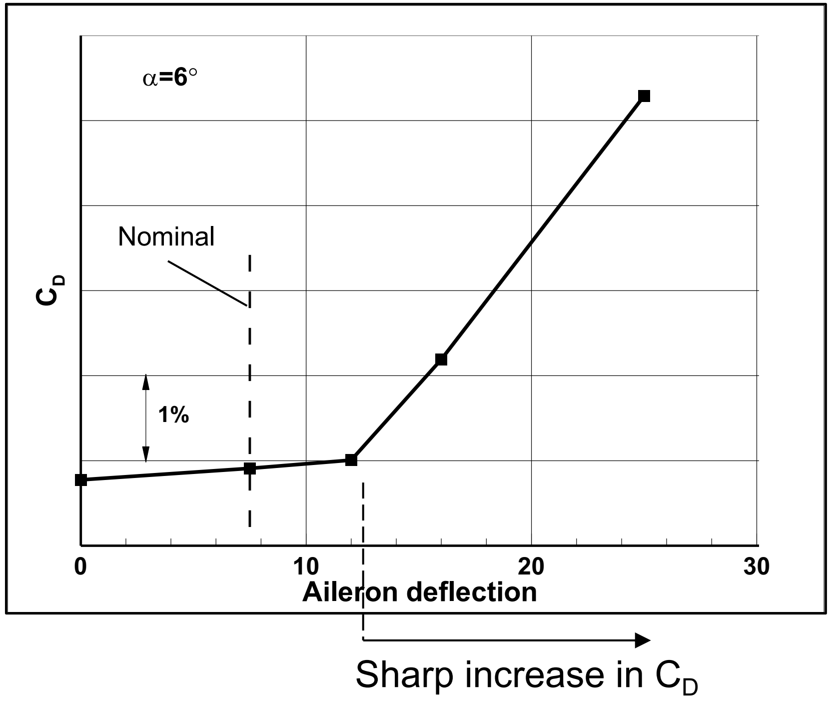


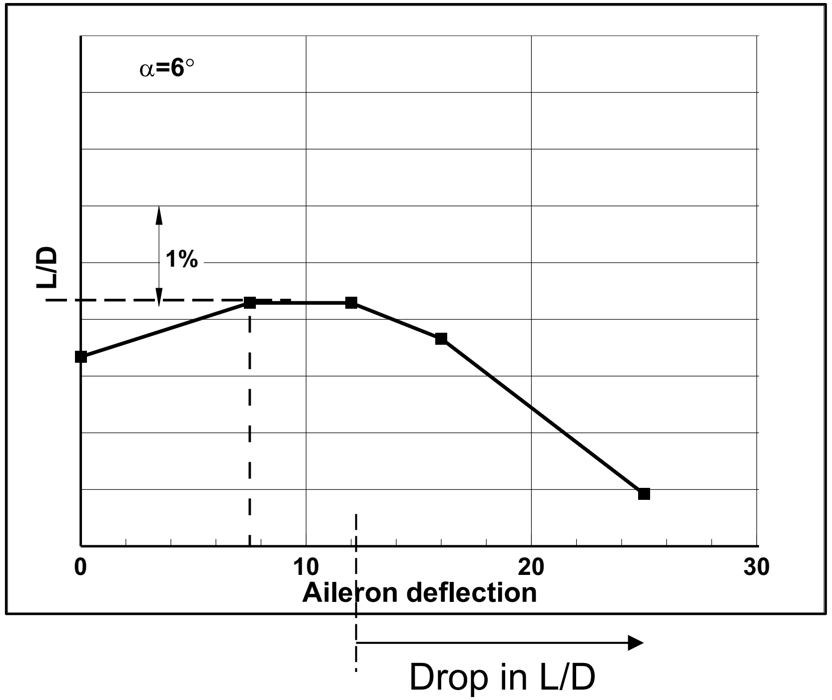
Aileron Deflections (Baseline, AFC off)

Motivation for AFC – augment L/D beyond the level achieved with the nominal deflection

Aileron deflections 0°, 7.5°, 12°, 16°, 25°







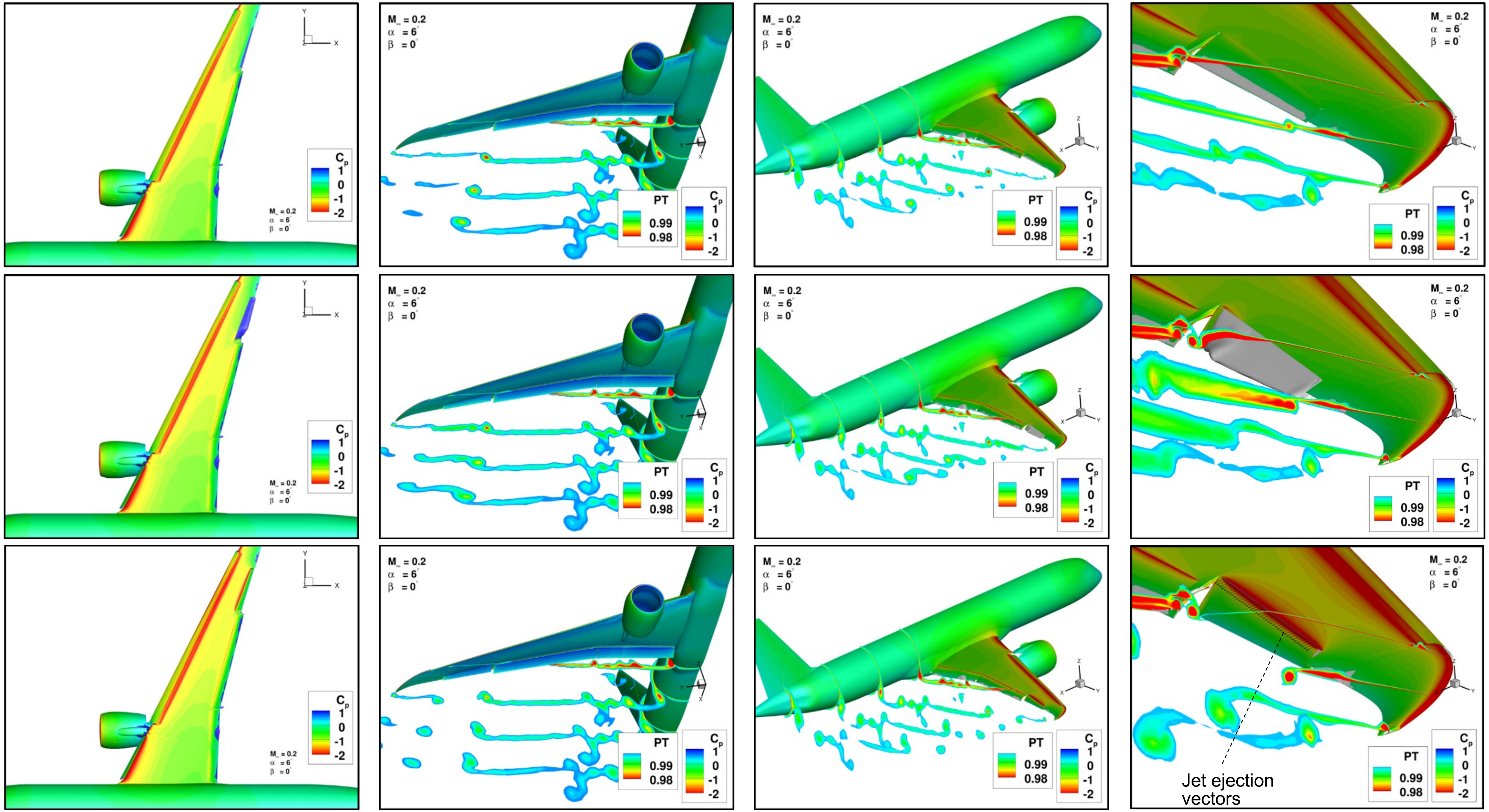
Effects of AFC – PR=2.0, Streamwise Jet

Surface BCs, Effective $h_{jet}/c_{midaileron}$≈0.008

Ail 7.5° (nominal)

Ail 25° AFC Off

Ail 25° AFC On



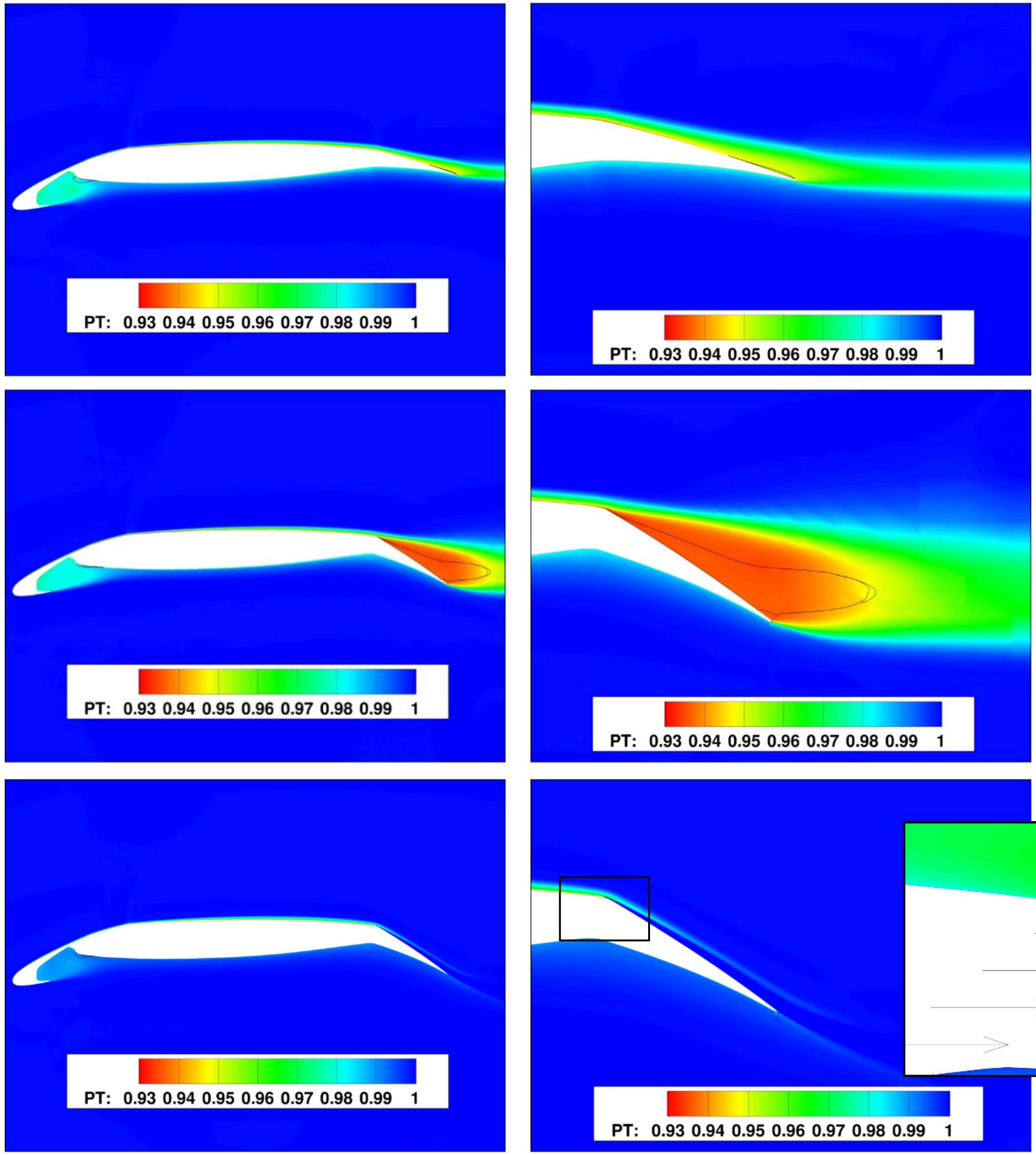
Effects of AFC – PR=2.0, Streamwise Jet

Midaileron cross-section

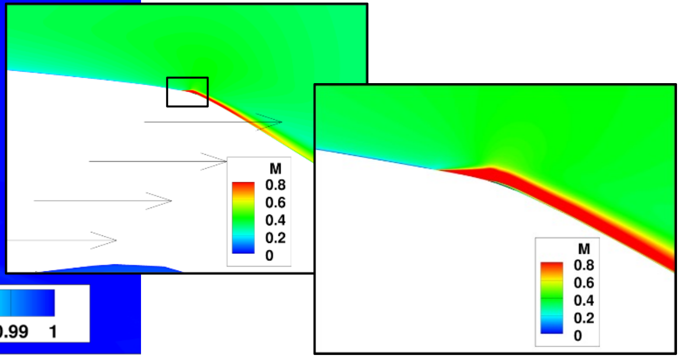
Ail 7.5°

Ail 25°
AFC Off

Ail 25°
AFC On



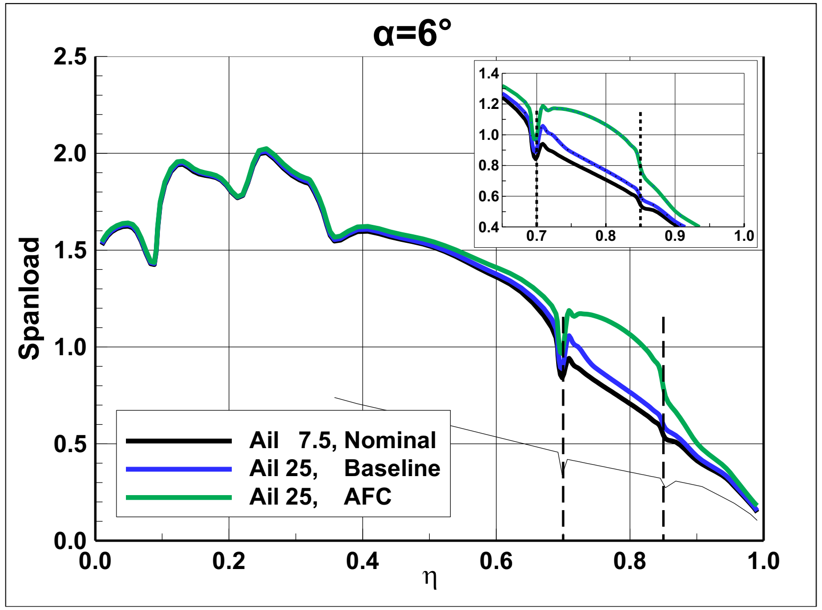
Black line – Flow reversal

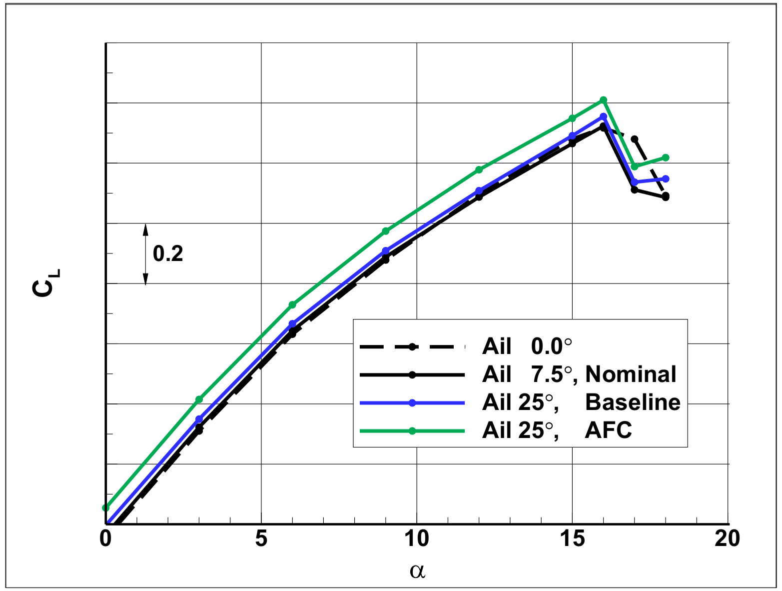


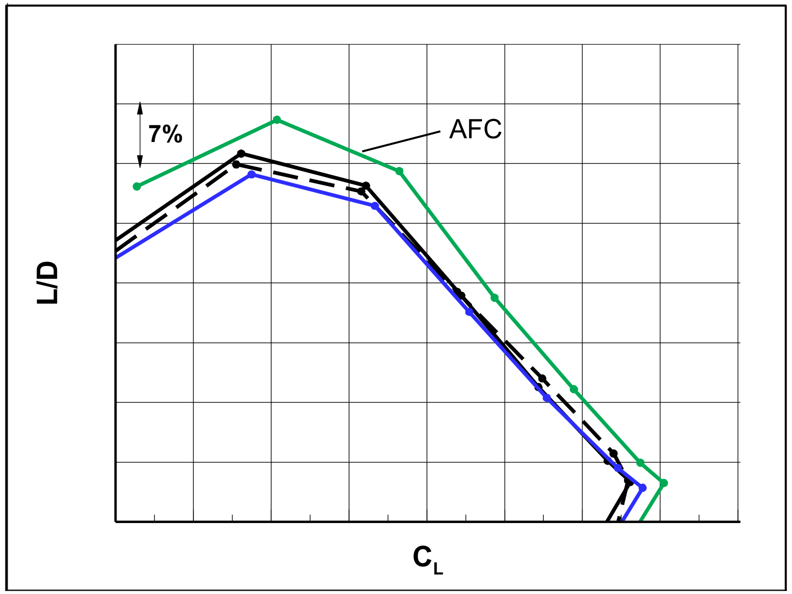
Effects of AFC – PR=2.0, Streamwise Jet

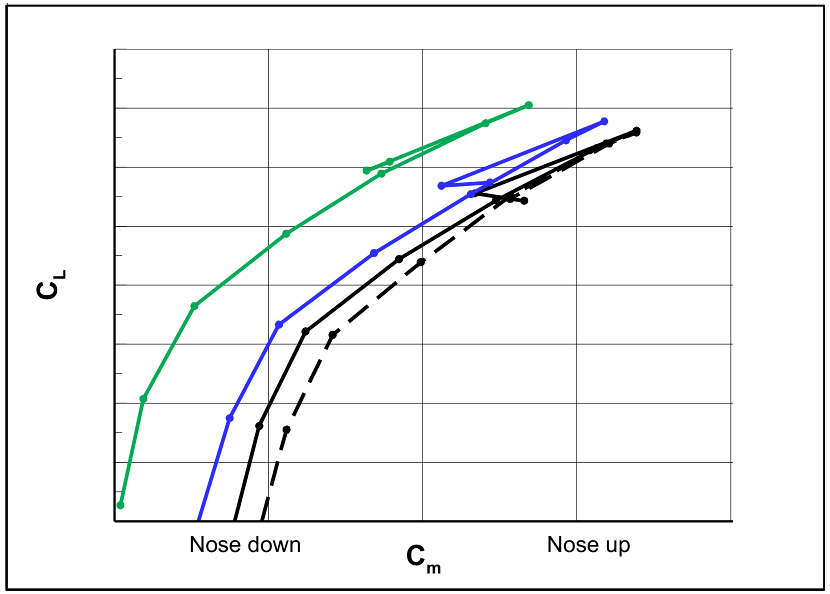
AFC impact on aero performance + integration

- \+ Increased C_L over the practical lift range, including $C_{L,max}$
- \+ Reduced flow separation + closer to elliptical spanload results in reduced drag
- \+ Hence significant increase in L/D is predicted
- – Aft loading results in increased nose-down pitching moment, resulting in potential trim drag penalty
- – Higher wing bending moments
- – Aeroelastic effects (negative twist)



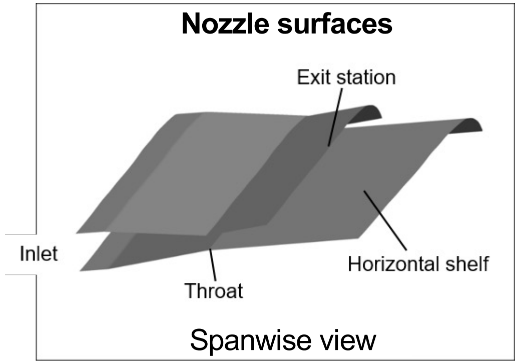


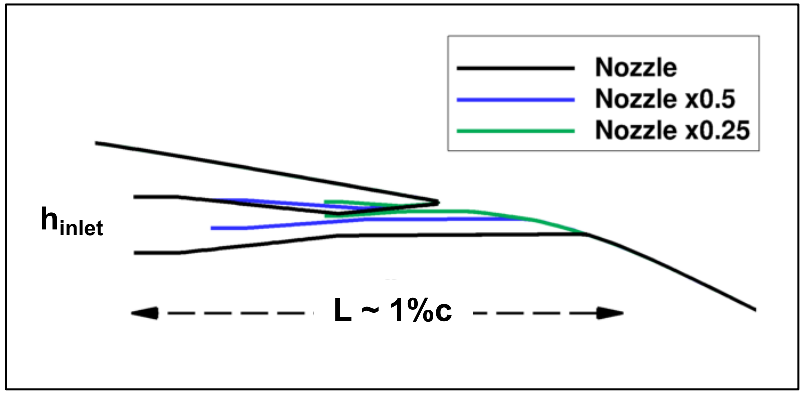




Convergent/Divergent (CD) Nozzle

- **Realistic implementation of AFC**
  - CD in the vertical plane
  - 2D nozzle cross-section identical along the span, edge-to-edge
  - Mild angle of the divergent section to prevent separation
- **Grid ~85 million**
- **Nozzle operates at low PR**
  - Nozzle area is large

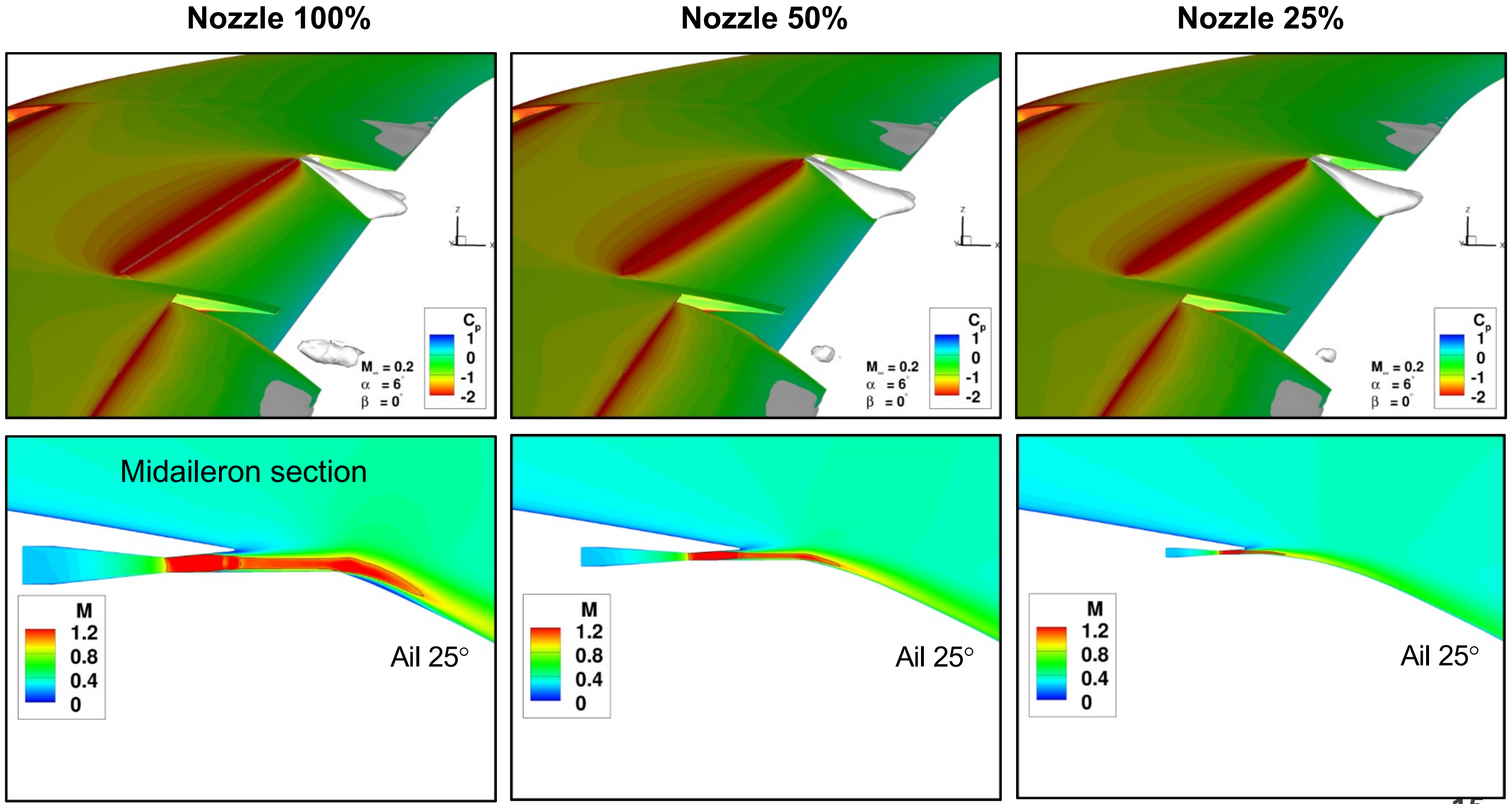




$h_{inlet}/L \approx 0.11$

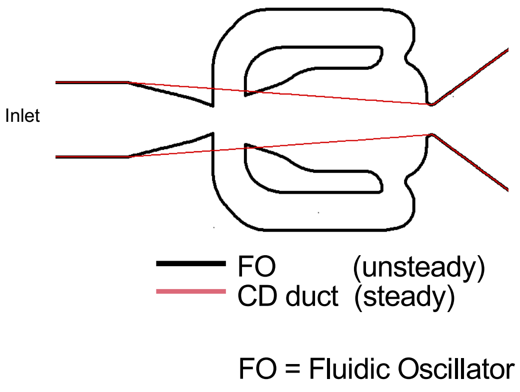
c = local wing chord

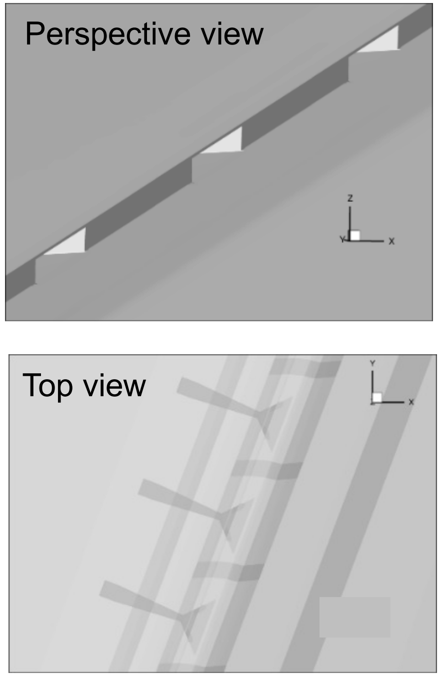
PR=2.0

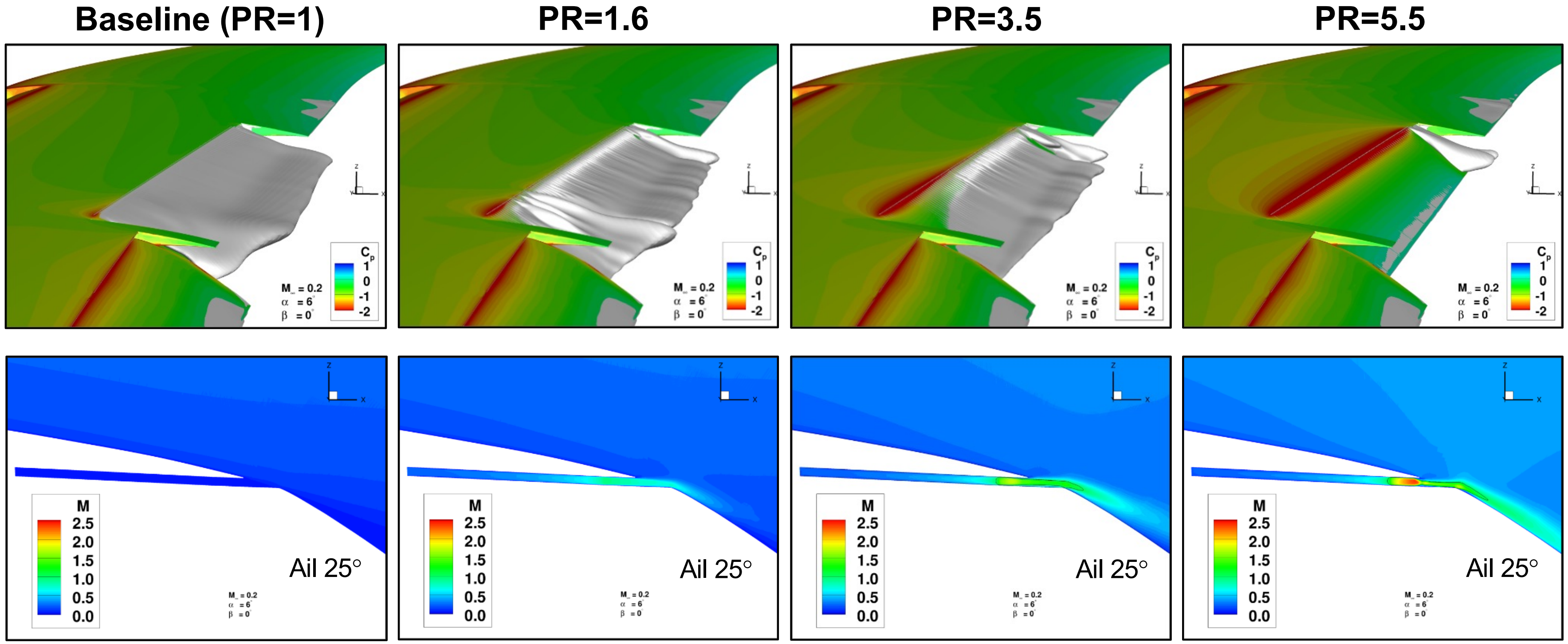


Discrete Convergent/Divergent Ducts

- **Derived from the NASA Fluidic Oscillators**
  - Are used in DARPA/CRANE X-65 AIAA 2023-2310, AIAA 2023-4310[1]
- **Convergent/divergent in wing planform**
- **Grid ~186 million**
- **Ducts are very efficient (reduced mass flow), but require high PR**
  - 78 ducts
  - Total duct area is very small





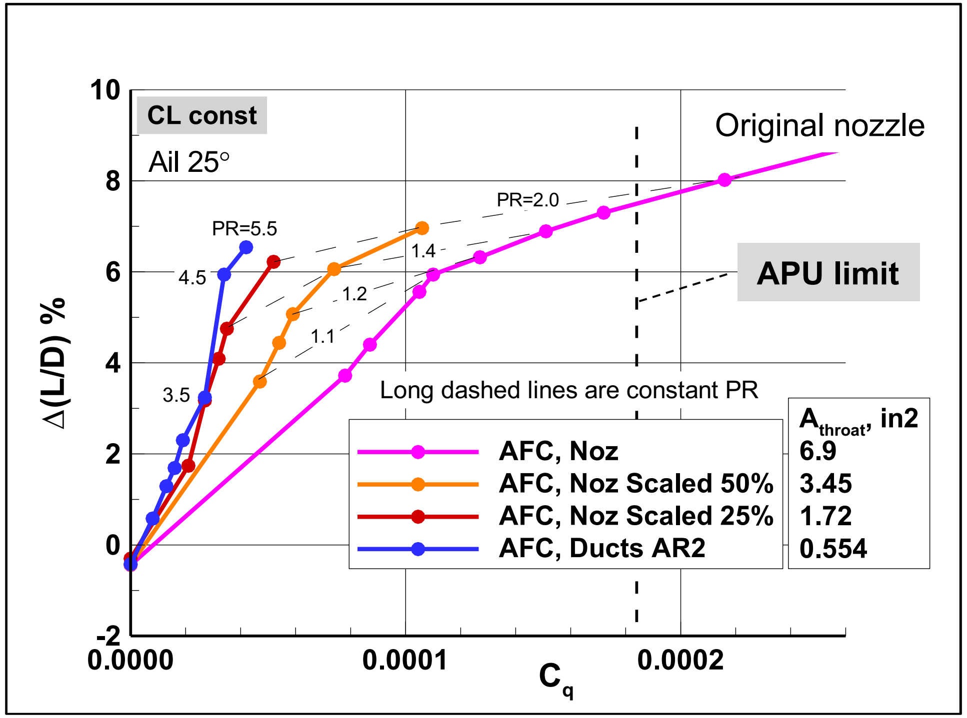


CRANE = Control of Revolutionary Aircraft with Novel Effectors

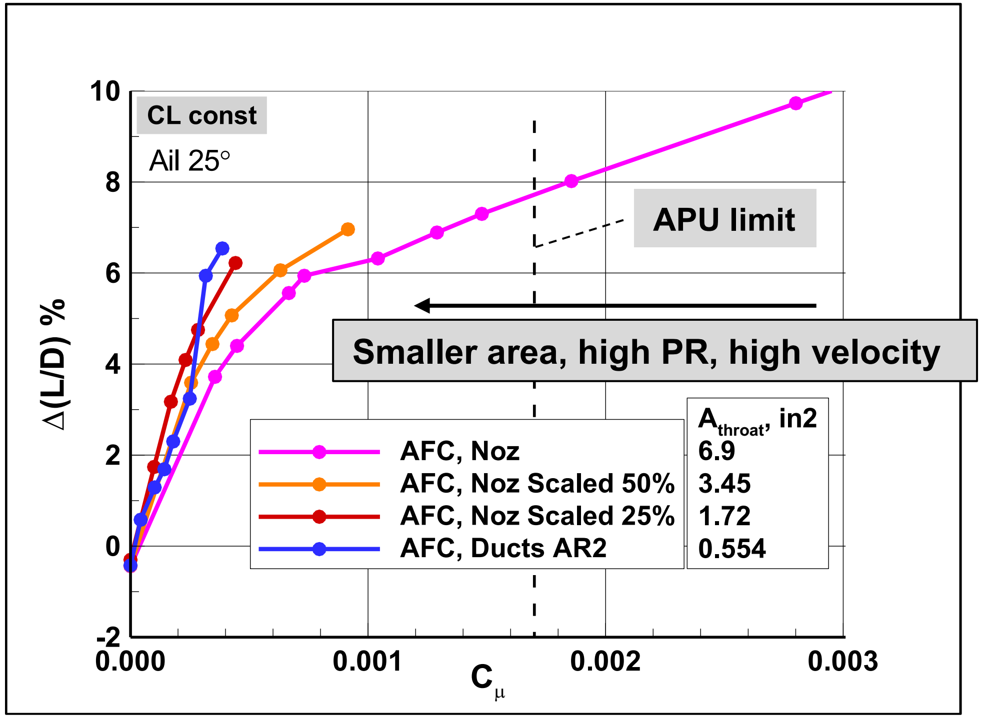
1 Shmilovich, Khodadoust, Colletti, Ansell, 'Steady versus Unsteady Pneumatic Flow Control and Aspects of Practical Integration'

Assessment of AFC Layouts – Nozzles vs Discrete Ducts

- **Both nozzles and discrete ducts are potential candidates**
- **Better performance is achieved with smaller area, but requires higher PR**
- **The available air source (PR, C_q, etc.) will drive the selection of nozzle type/size**



Mass flow coefficient



Momentum coefficient

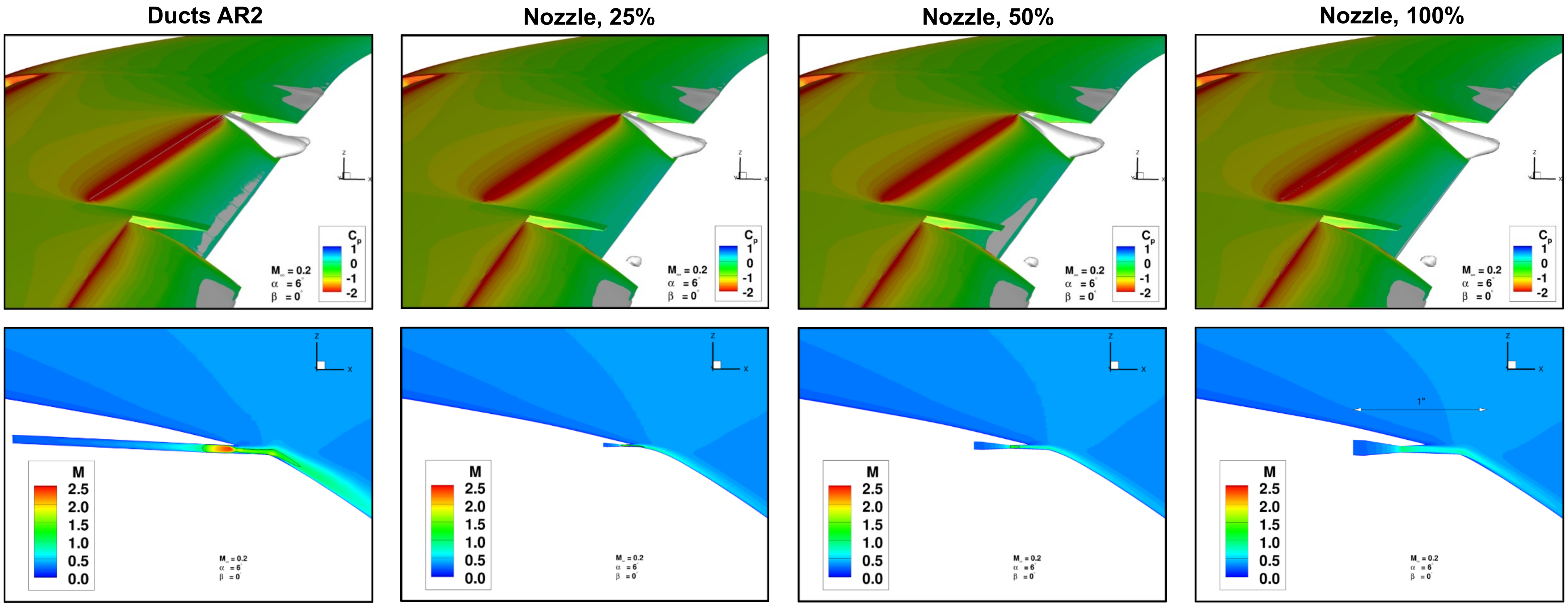
ΔL/D~6% achievable with onboard supply

APU = auxiliary power unit

Aspects of Integration

Actuation types will be paired up with potential sources

Aileron 25°

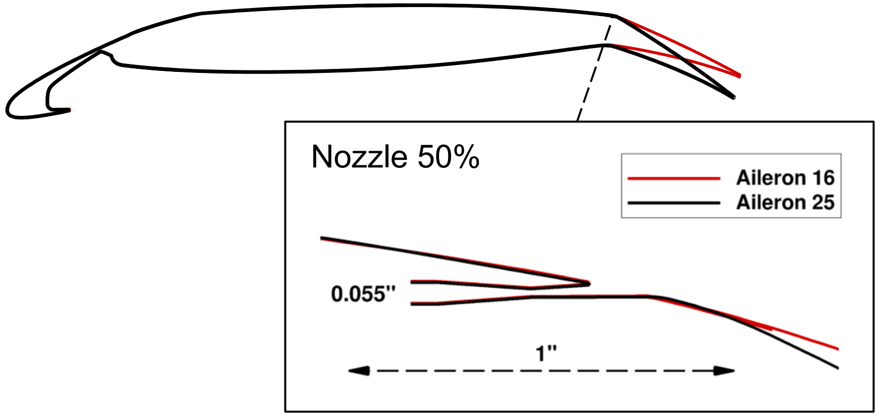


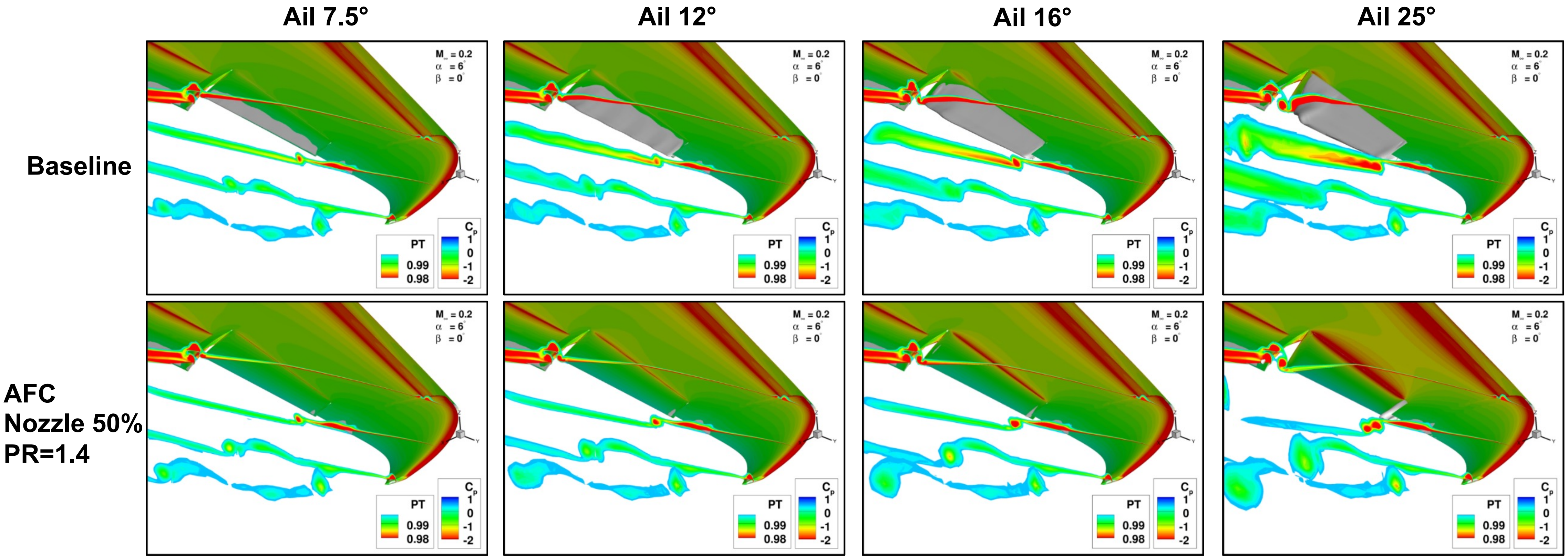
APU, Engine Bleed ⟷ **Compressors**

Smaller	**Area**	Larger
Lower	**Massflow**	Higher
Higher	**Pressure**	Lower
Higher	**Velocity**	Lower

More Practical Aileron Deflections

- **Consider lower deflections** (25° was used up to this point)
  - More acceptable hinge moments for aileron actuators
  - Lower wing bending moments
  - Lower trim drag

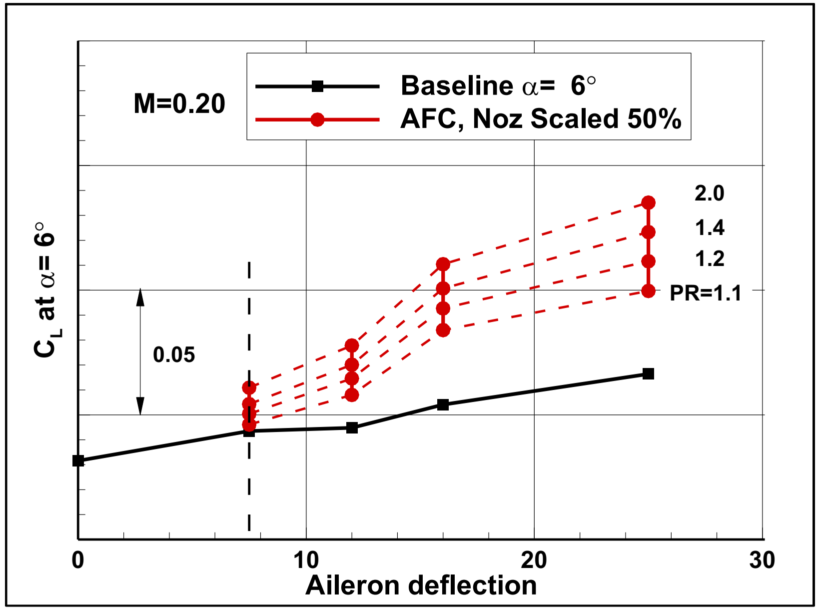


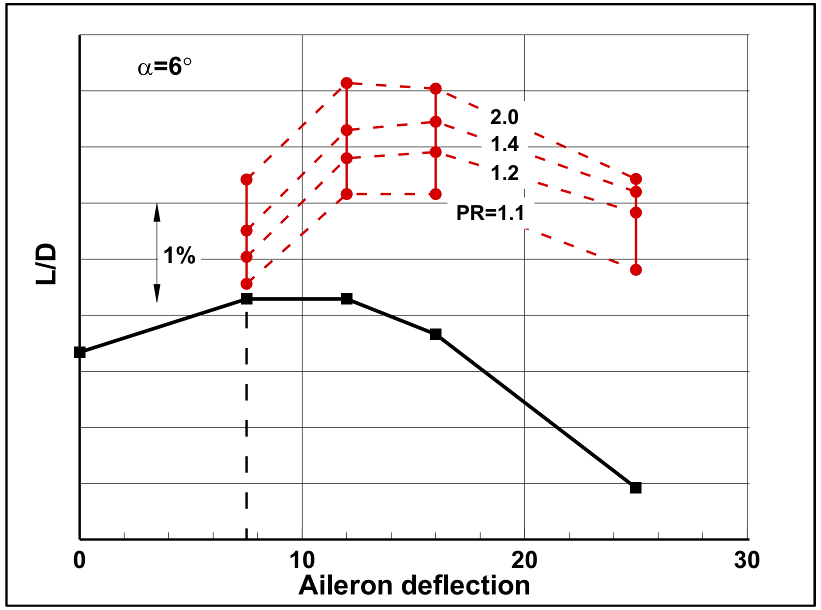


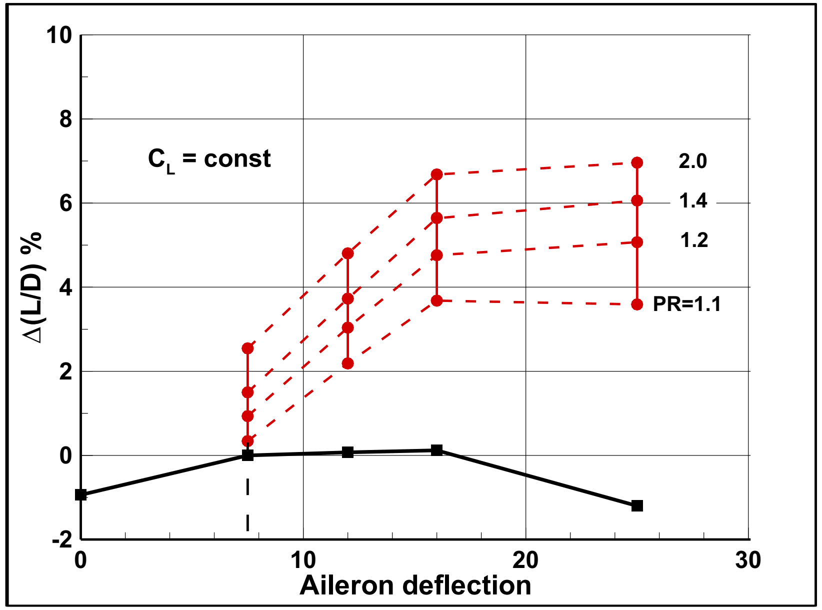
Δ(L/D) = 1.5%   Δ(L/D) = 3.73%   Δ(L/D) = 5.64%   Δ(L/D) = 6.06%

Effects of Aileron Deflections (Nozzle 50%)

- **The best aero performance is in the range of 16°-25° (takeoff flap setting)**
  - Proportionately smaller gains at 12° and 7.5°
- **Selection of aileron deflection will likely be influenced by integration factors**



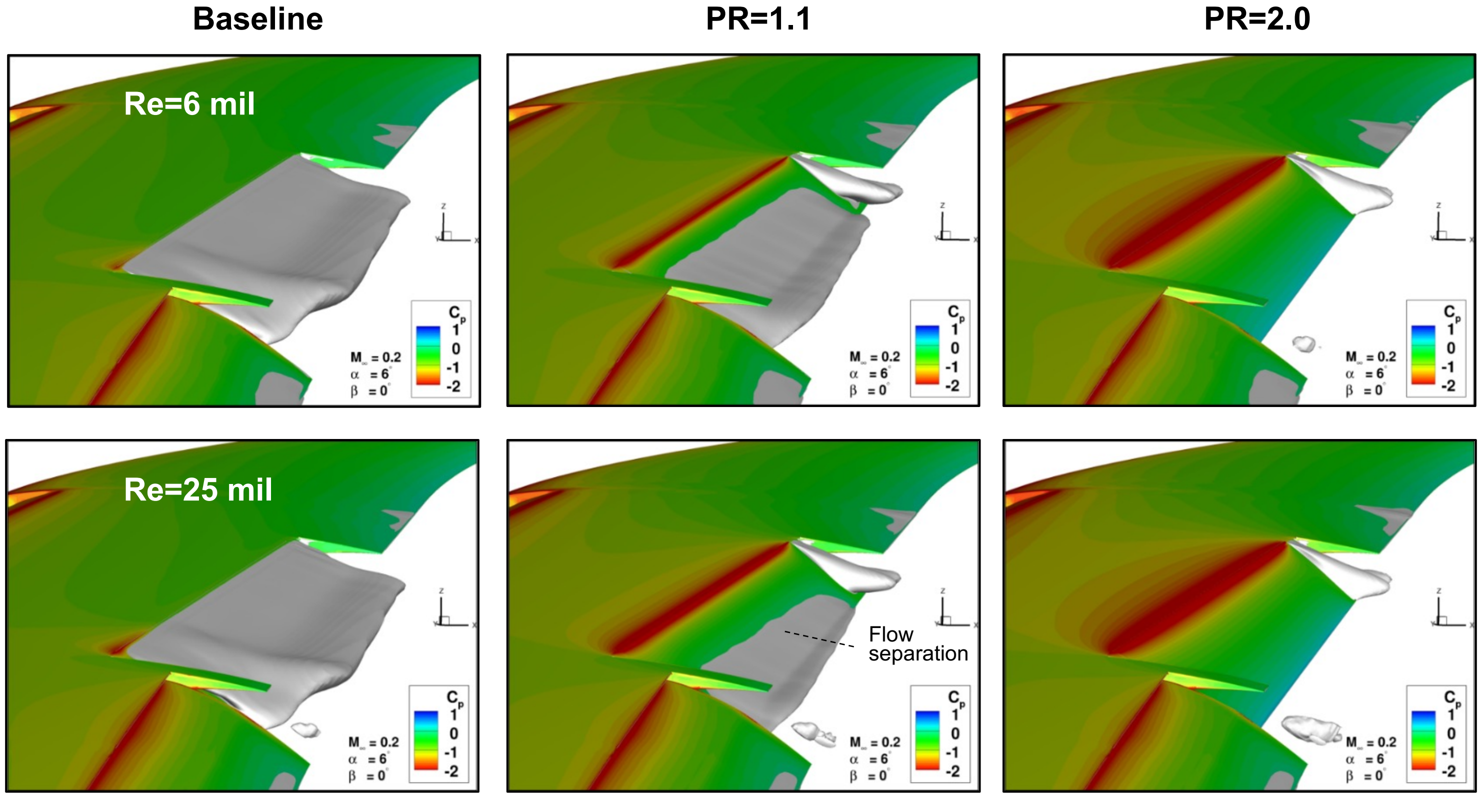


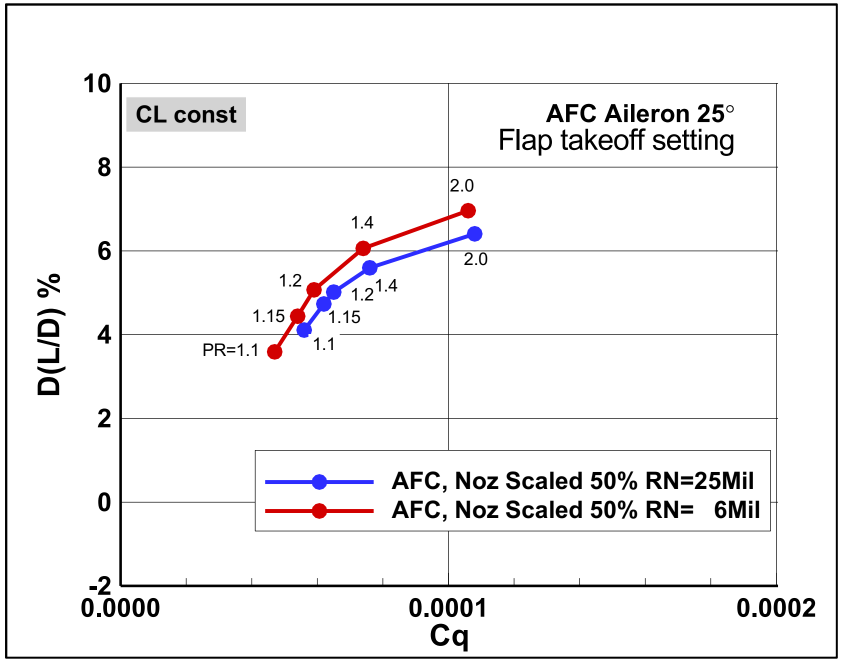


Maximum L/D gain is achievable with aileron 16°

Reynolds Number Effects

Lower viscous effects at high RN results in slightly reduced AFC effects

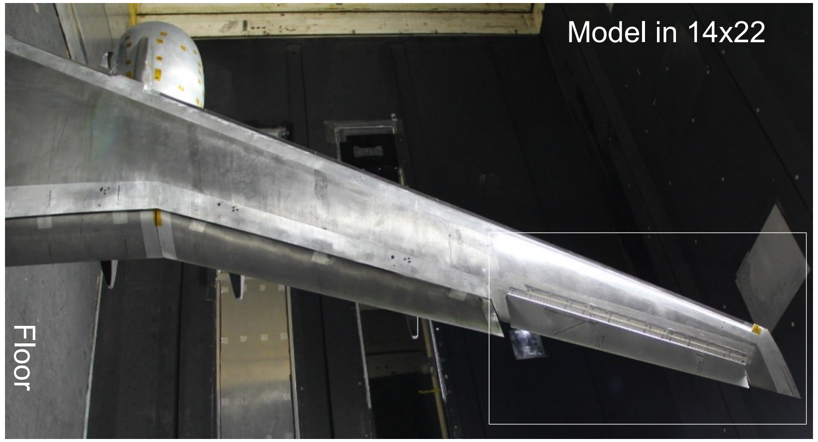


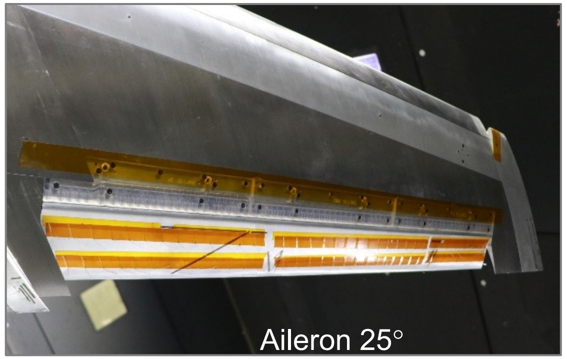


M_∞=0.20
α=6°

Conclusions – Aileron at Takeoff

- **Both elongated CD-nozzles and discrete CD-ducts are promising candidates**
- **Gains in L/D ~6% and $C_{L,max}$ ~2.5% can be achieved with onboard sources**
- **Significant gains are obtained at smaller aileron deflections**
  - Ease of integration
- **Flight Reynolds number indicates slightly reduced AFC effects**
- **Landing results in similar AFC effects**
- **Experimental confirmation of the AFC approach is currently underway**
  - CRM-HL tested at the NASA LaRC 14x22 tunnel (Feb.-March 2023)





CRM-HL = Common Research Model - High Lift

Boeing Research & Technology

Dreaming
Collaborating
Innovating
Exploring
Trailblazing

Applications of Flow Control to Wing High-Lift Leading Edge Devices on a Commercial Aircraft

Arvin Shmilovich[1], Yoram Yadlin[1], Paul Vijgen[2], Rene Woszidlo[1]
[1] Boeing Research and Technology
[2] Boeing Commercial Aircraft (Retired)

AIAA SCITECH 2023
AIAA-2023-0656
Session: APA-24, Flow Control Applications
Including Experiment and Computation IV
Tuesday Jan 24, 2023

Producing
Leading
Creating
Researching
Analyzing

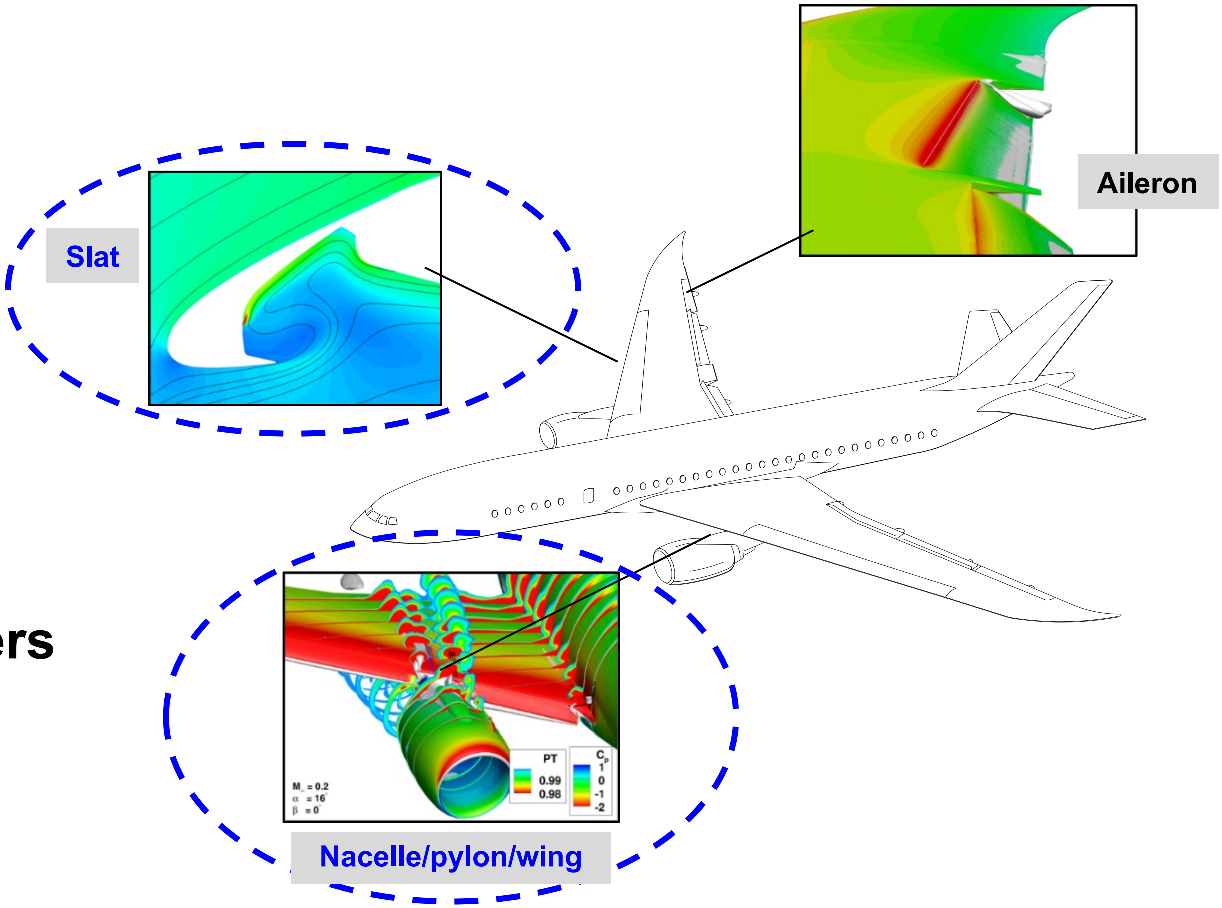
Motivation

- **Improve airplane performance by increasing L/D, C_L, $C_{L,max}$ during high-lift**
  - **Higher payload, longer range, shorter runway** (AIAA 1991-1527)
    - A 1.5% increase in $C_{L,max}$ is equivalent to a 6,600lbs increase in payload for a fixed approach speed
    - Δ(L/D) = +1% in takeoff is equivalent to a 2,800lbs increase in payload or a 150nm increase in range

- **Localized AFC concepts**
  - **Aileron**
  - **Wing Leading Edge**
    - Slat
    - Nacelle/pylon/wing

- **NASA/Boeing collaboration**
  - **NASA PMs – John Lin, Latunia Melton**
  - **Boeing PM – Rene Woszidlo**

- **Study described in three SciTech 2023 papers**
  1. **Aileron** AIAA 2023-0655
  2. **Wing LEs** AIAA 2023-0656
  3. **System Integration** AIAA 2023-0657

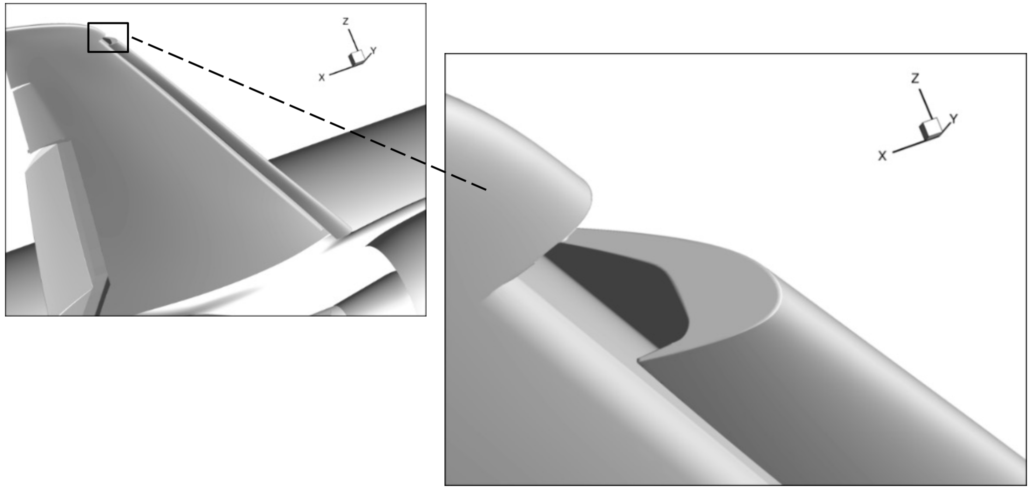


AFC = Active Flow Control

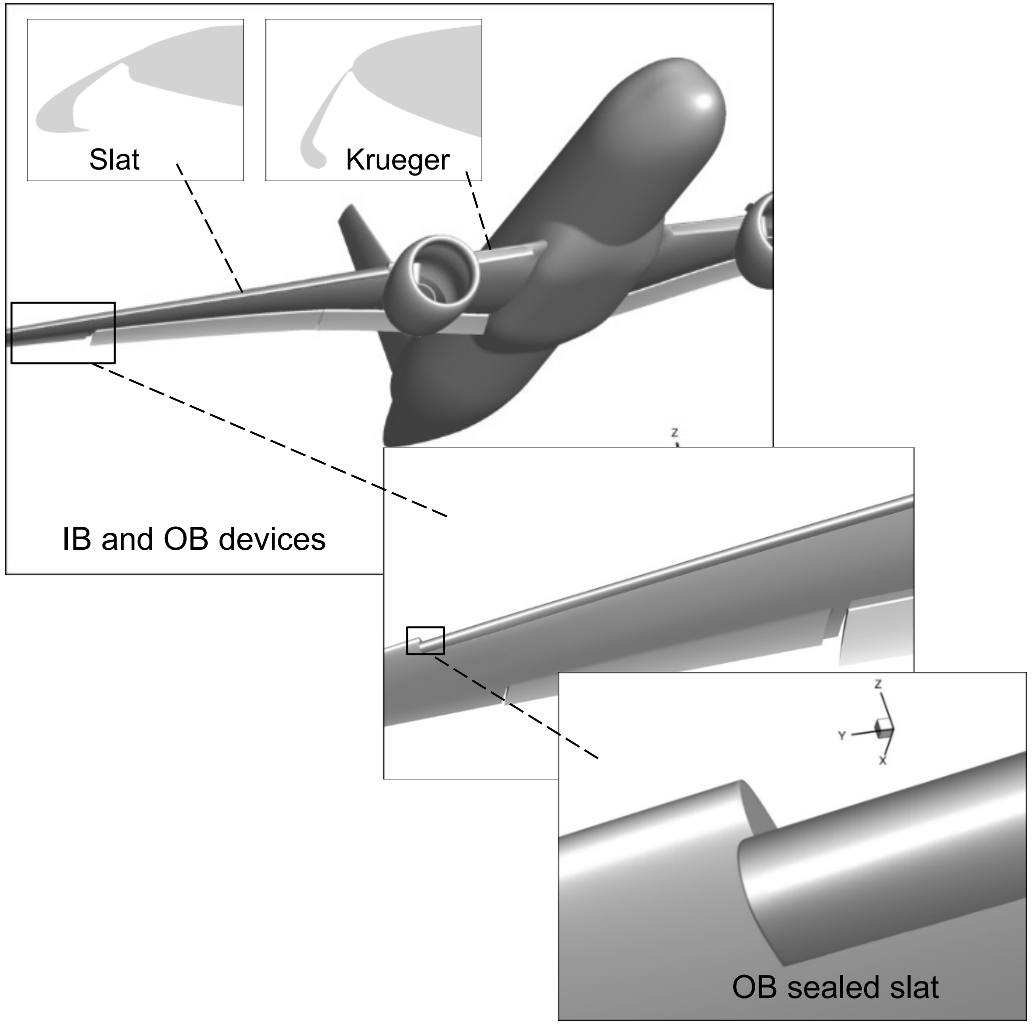
Reference Aircraft

Notional short/medium-range twin engine airplane

- High-lift system – Krueger/slats, single-slotted flap, nacelle chine
- Takeoff flap setting



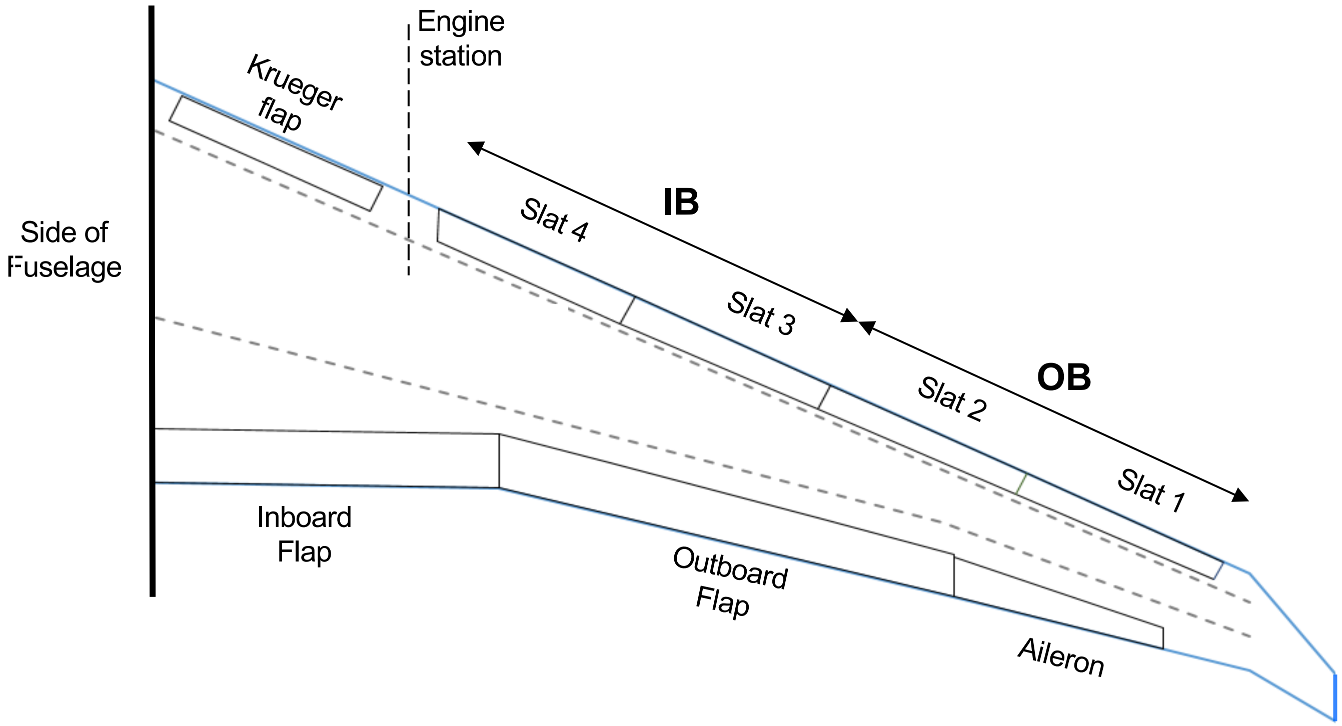
Sealed slats at takeoff



OB = outboard
IB = inboard

Potential Fluidic Sources

- **Proximity to potential fluidic sources are an important factor for the design of an AFC system**
- **Potential sources at the engine strut**
  - Engine bleed
  - APU
  - Wing anti-ice system (WAI)
    - Selected slats are equipped with WAI, which is a source of hot air (high T helps reduce mdot)
  - Local compressors

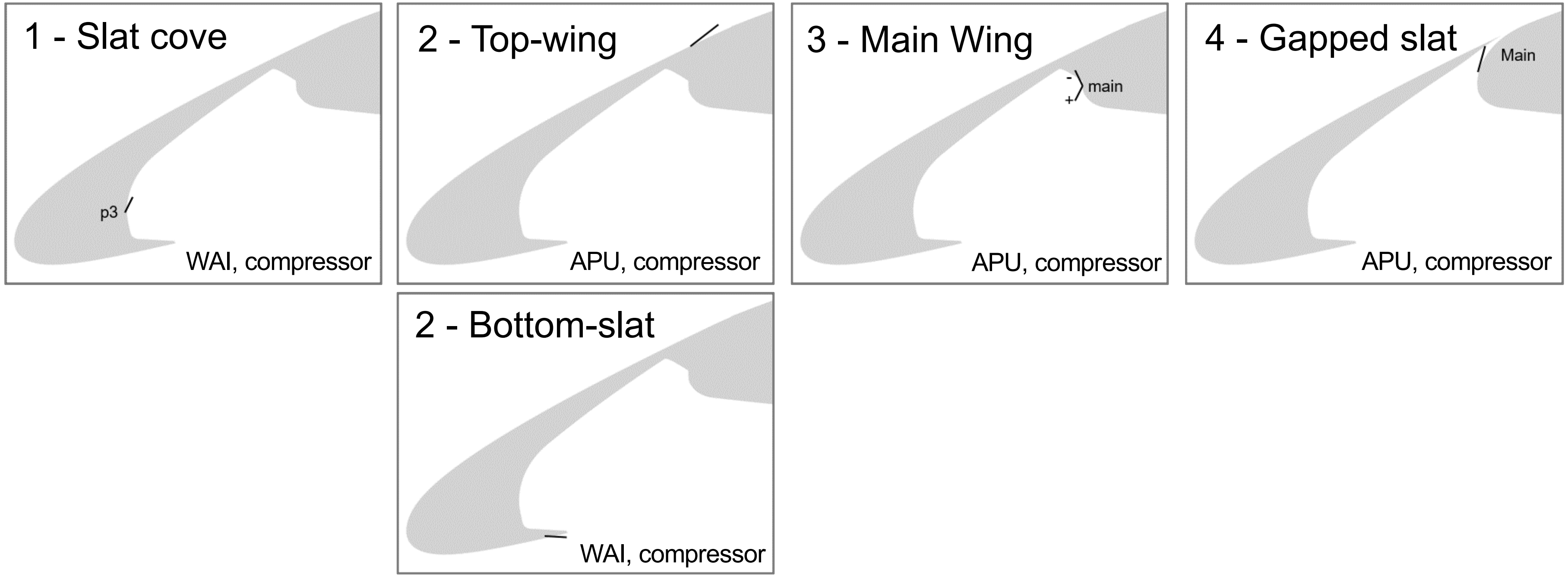


APU = Auxiliary Power Unit
WAI = Wing Anti-Ice

AFC at the Slats

Targeted Slat Applications

- **Leverage the experience from AIAA 2020-0784**
- **Several AFC layouts have been considered**

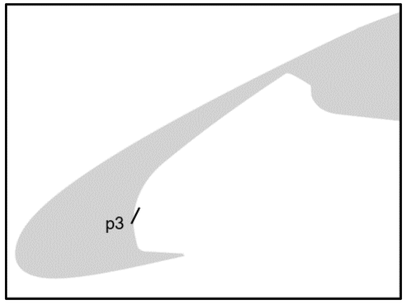


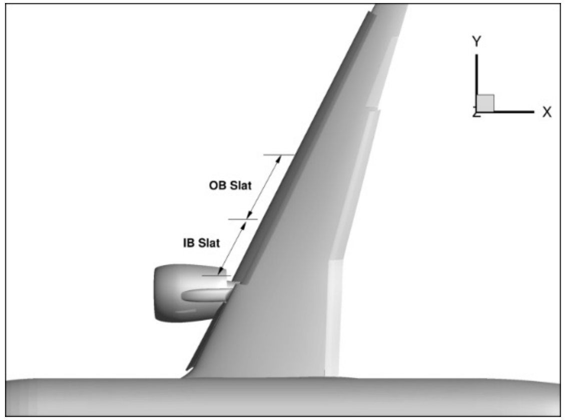
- **Layouts 1 and 4 will be described here**
- **AFC with surface BCs**

APU = Auxiliary Power Unit
WAI = Wing Anti-Ice

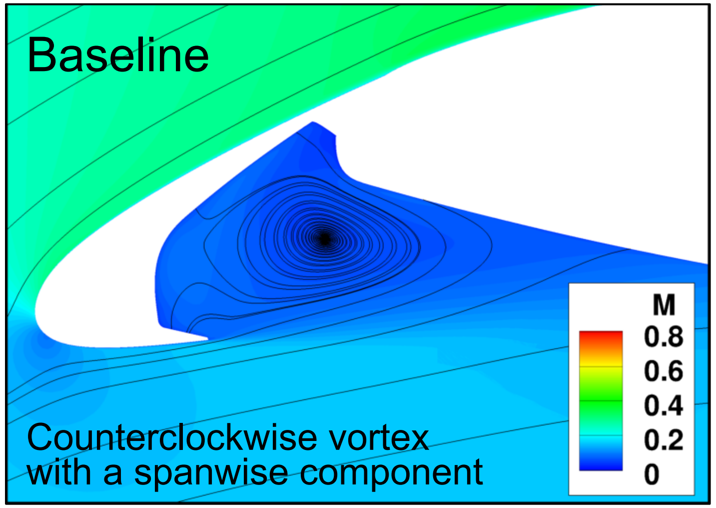
1 - Slat Cove

- **Numerical setup**
  - Fine mesh ~100 million points
  - Surface BC
  - Jet efflux is at 20° off the local surface tangent in the upward direction

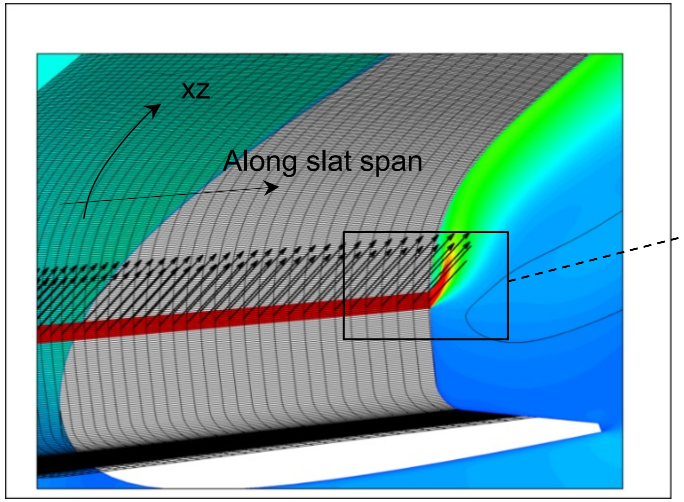




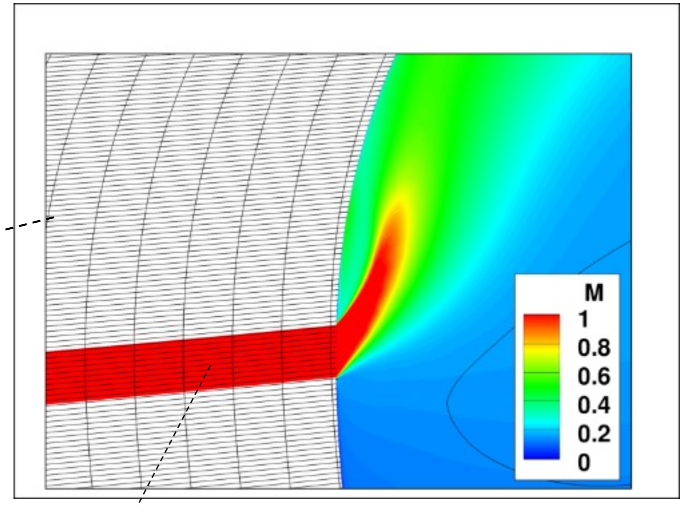
Slats 3 and 4



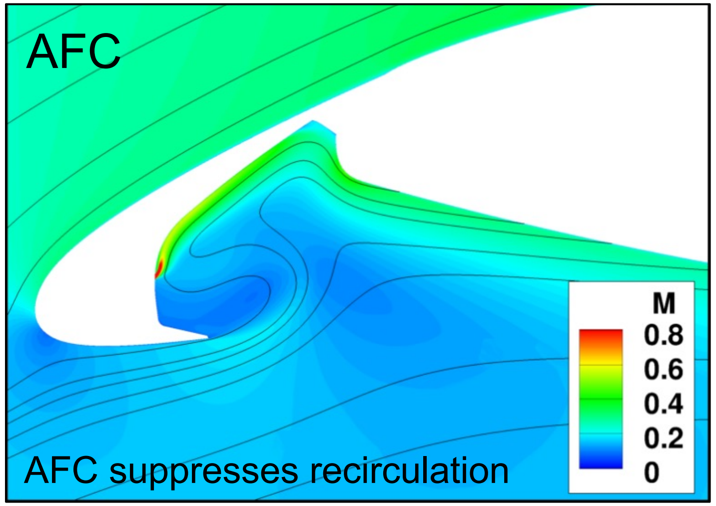
M contours are shown on a vertical streamwise cut at the mid OB slat



Every other 4 grid lines are shown in the xz direction



Jet conditions are defined by PT, TT and jet angle

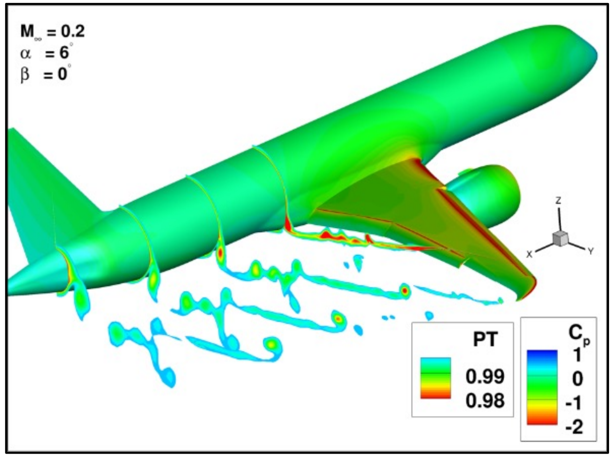


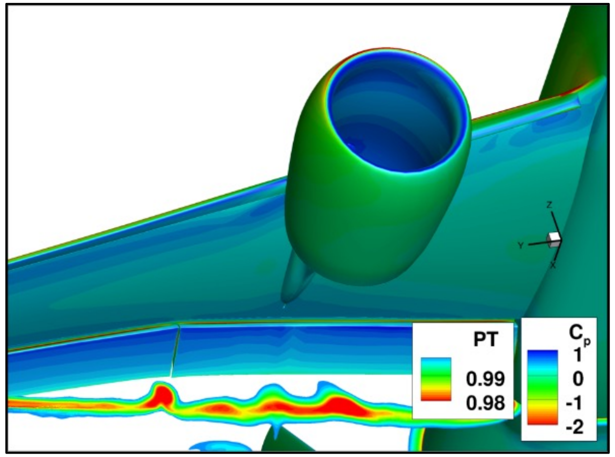
1 - Slat Cove

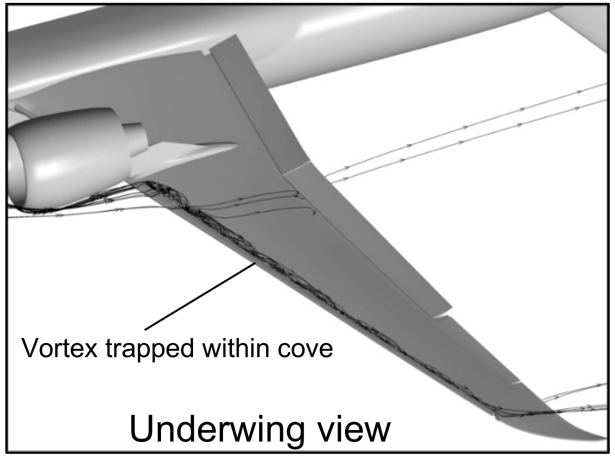
Cp = on surfaces
PT = Normalized total pressure on cuts

Baseline

- Flow is predominantly 3D in the vicinity of the slat
- Vortical flow forms in the slat cove and it emerges into the ambient flow towards the wing tip

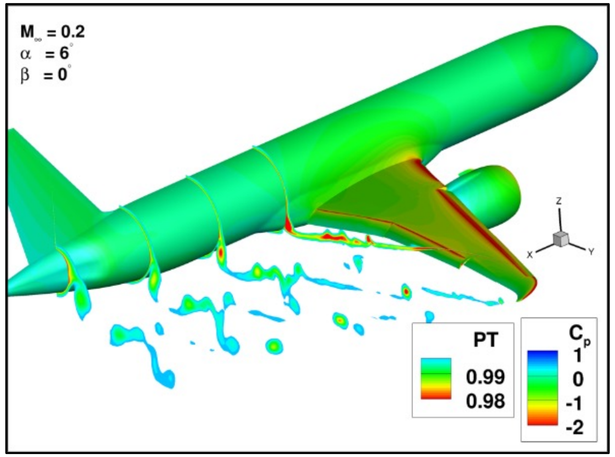


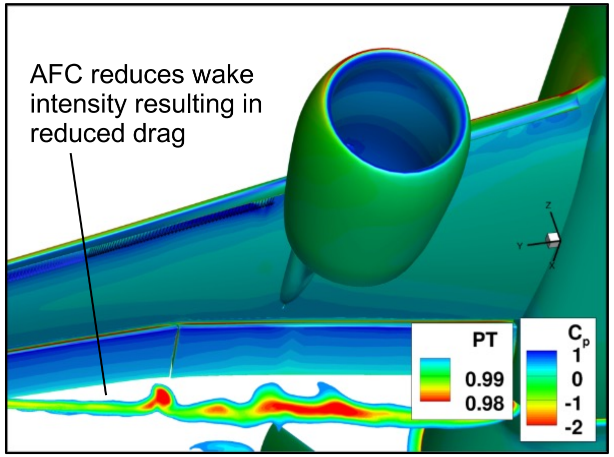


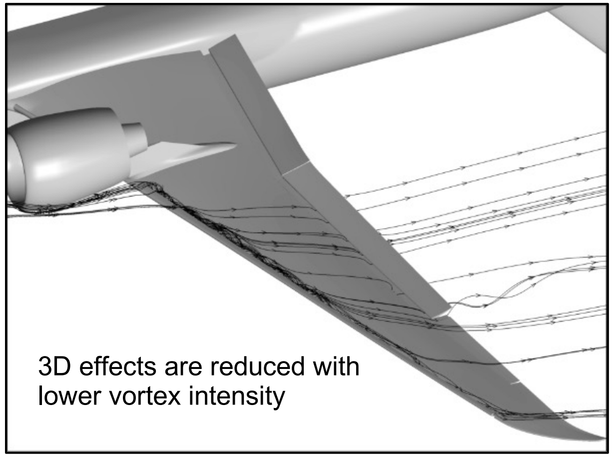


AFC

- Helps break the original counterclockwise flow, and helps curb spanwise flow and reduce 3D effects



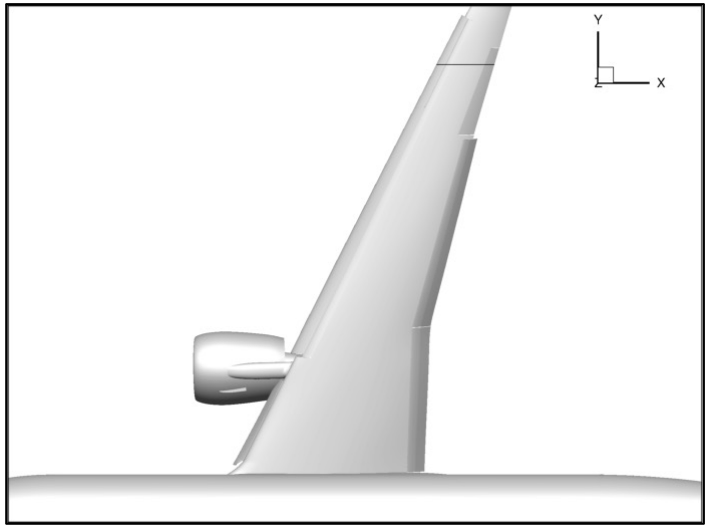


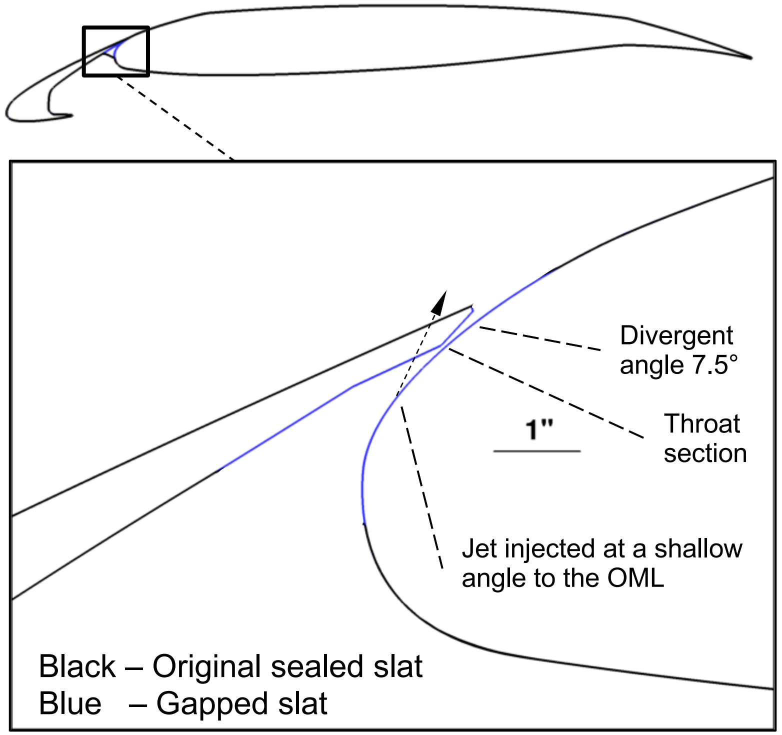


4 - Gapped Slat

Geometry setup

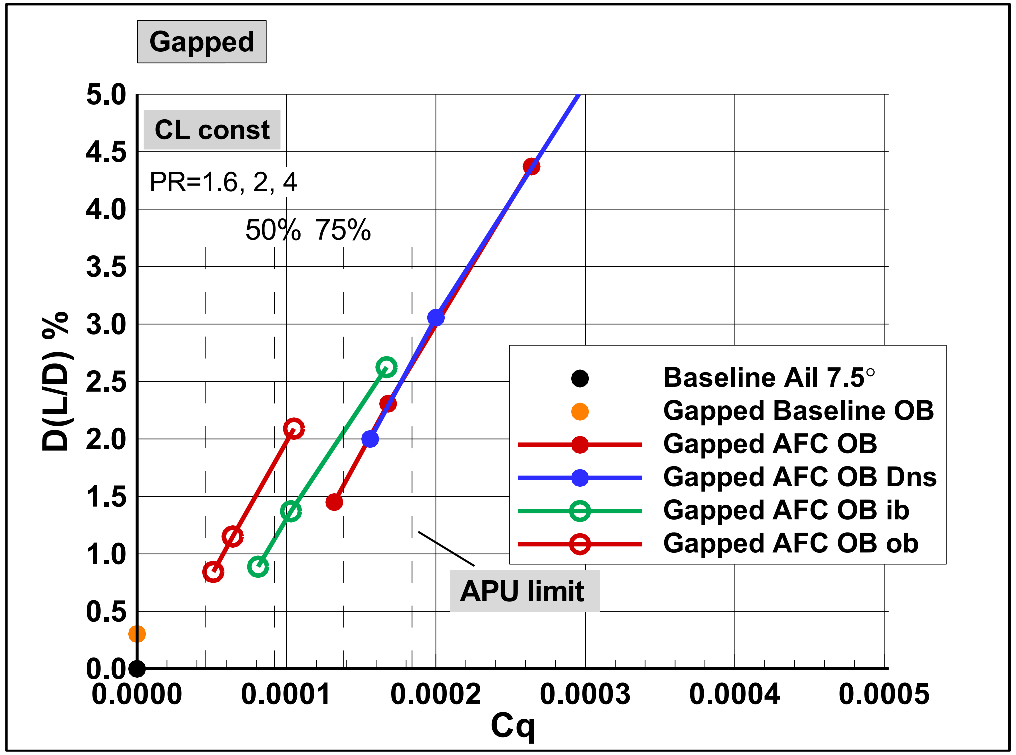
– Slat held at the same detent as in the sealed position
  - Preserves the general aero characteristics of the original wing
– Slat lower surface is modified to incorporate a convergent/divergent section

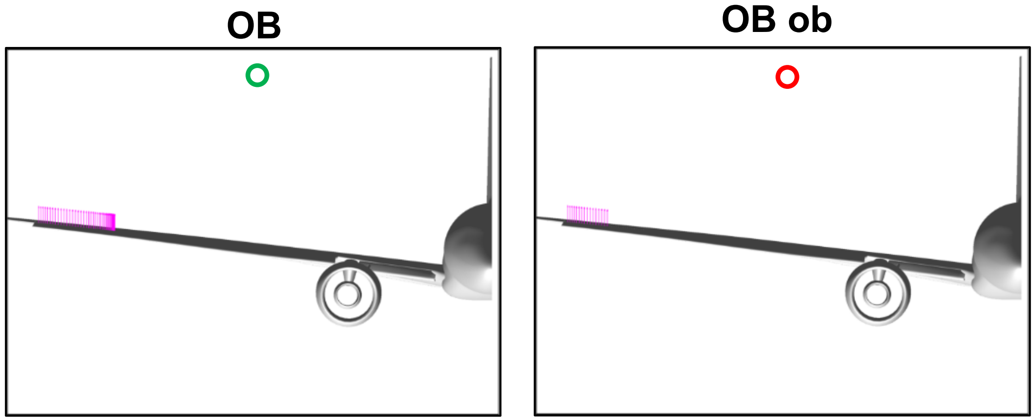




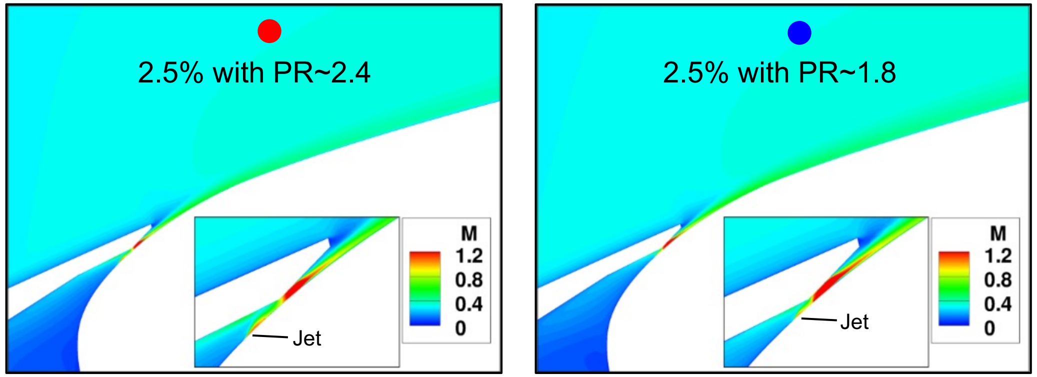
4 - Gapped Slat

- **Various AFC layouts land in the range of practical supply**





Outboard actuation 'OB ob' is more effective



Downstream actuation is more effective

ΔL/D up to ~2.5% achievable with onboard supply

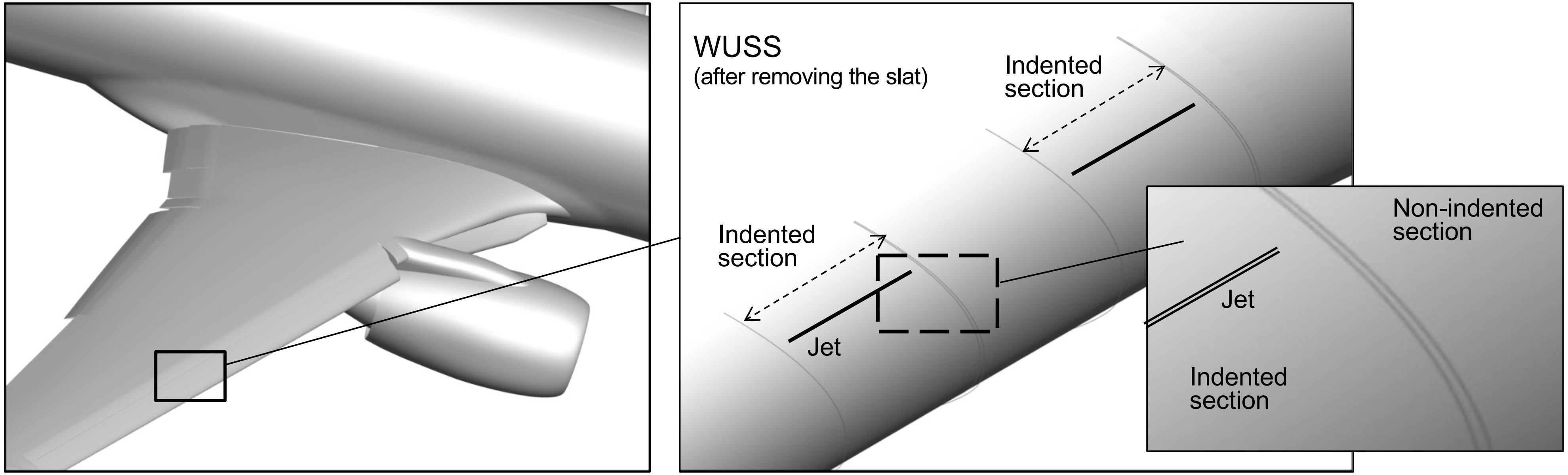
Potential solution for wing-tip separation at high-α

4 - Gapped Slat

Alternative implementation

- Wing can be modified
  - Designed to produce a convergent section

Potential mitigation of high-α wing tip separation



When the slat is in the sealed position

- Indented sections become gapped
- Non-indented sections remain fully sealed

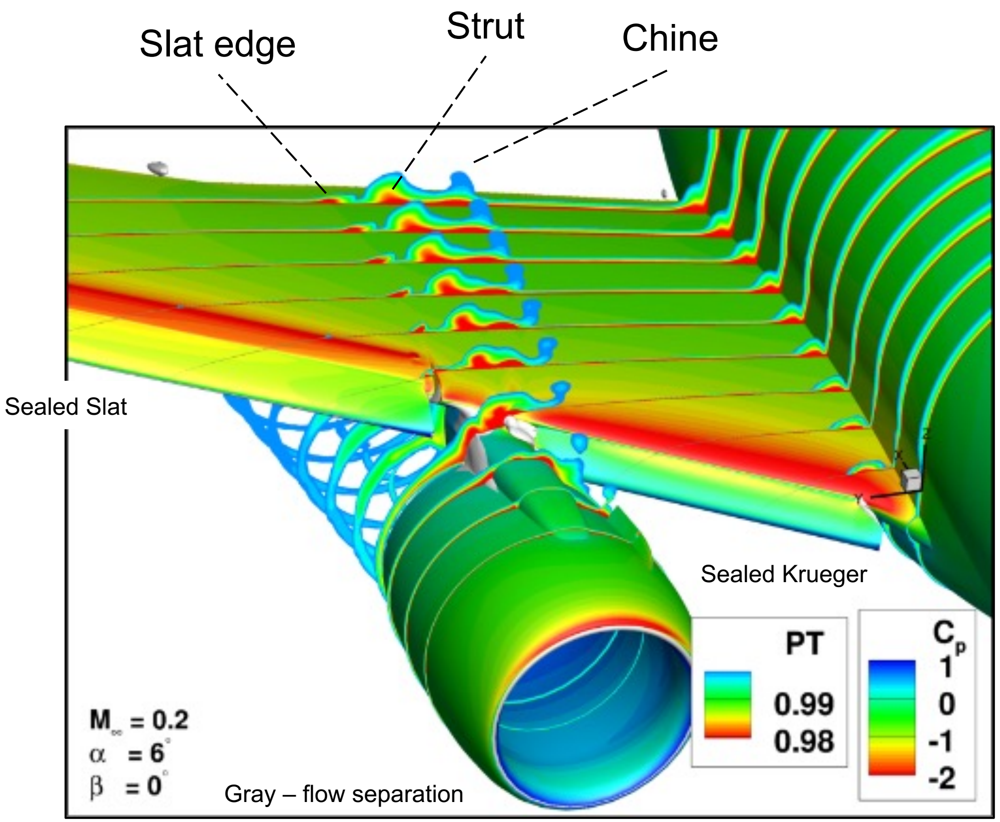
WUSS = Wing Under Slat Surface

AFC at Nacelle/Pylon/Wing

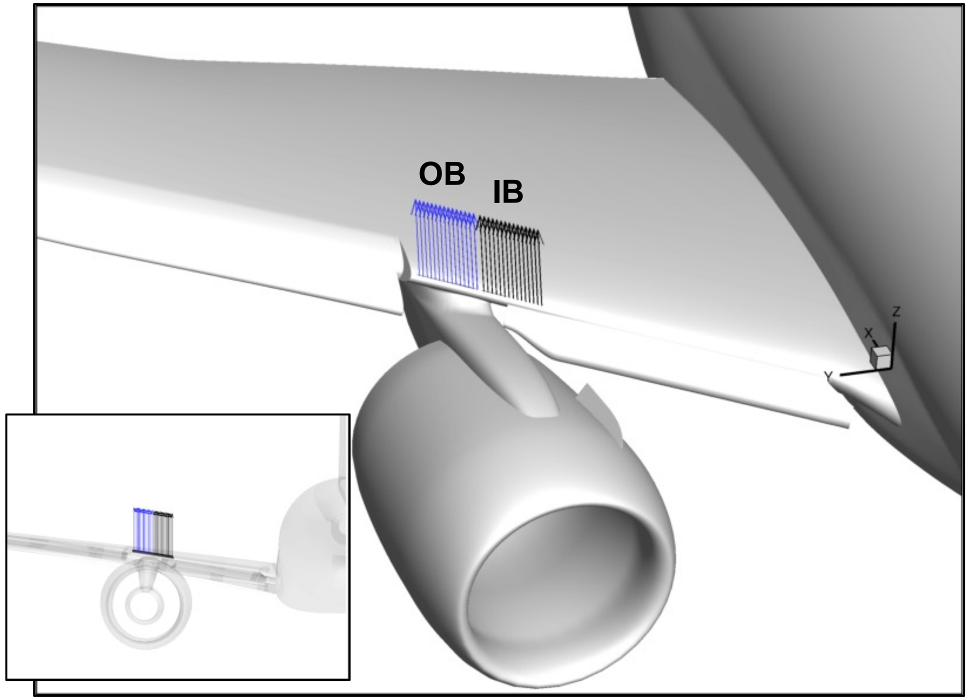
Nacelle/Pylon/Wing

Objectives

- Reduce wing/nacelle interference effects
- Potentially enabling better integration with the high-lift system at the pylon-engine
  - Especially important for integration of UHBR engines in future airplanes (reduced weight, maintenance)



Baseline

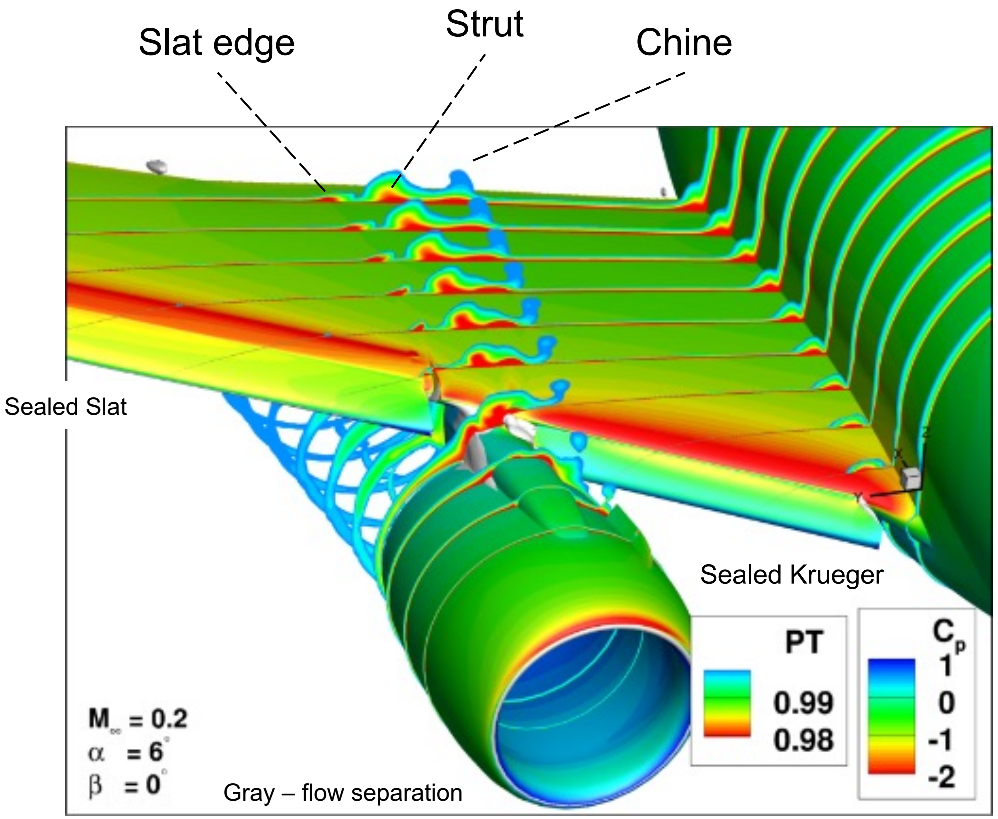


AFC Placement
On the fixed wing LE on both sides of the pylon station

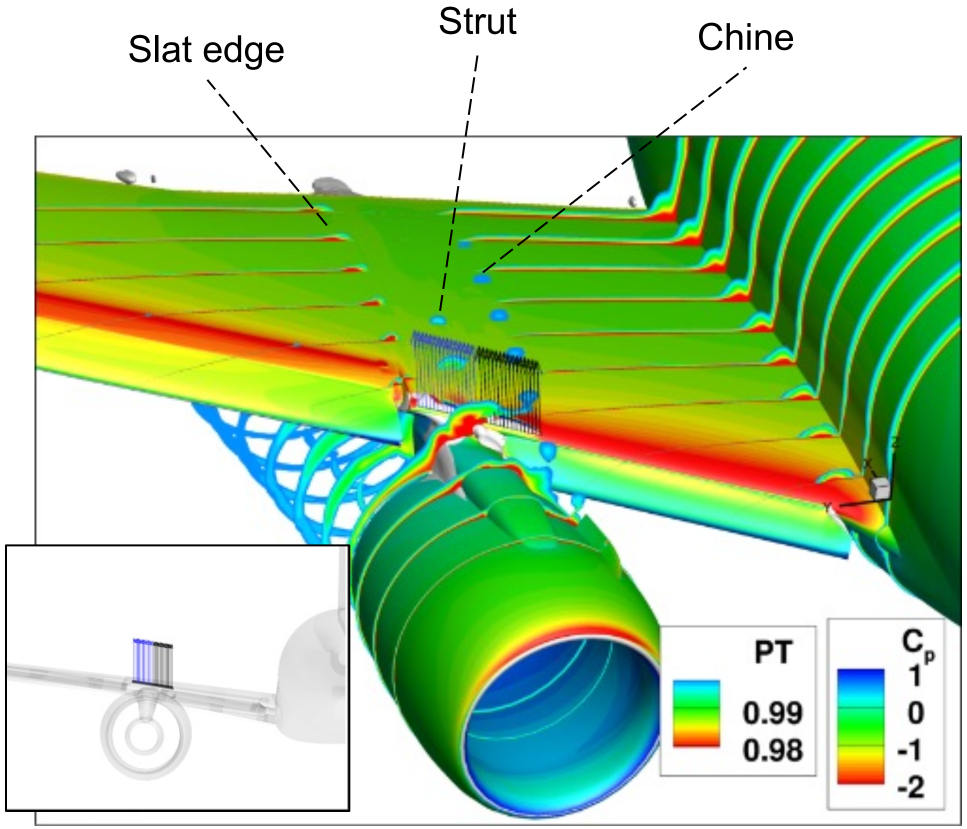
UHBR = Ultra High Bypass Ratio

Nacelle/Pylon/Wing at α=6°

Intensity of vortex elements and wake is substantially reduced by actuation



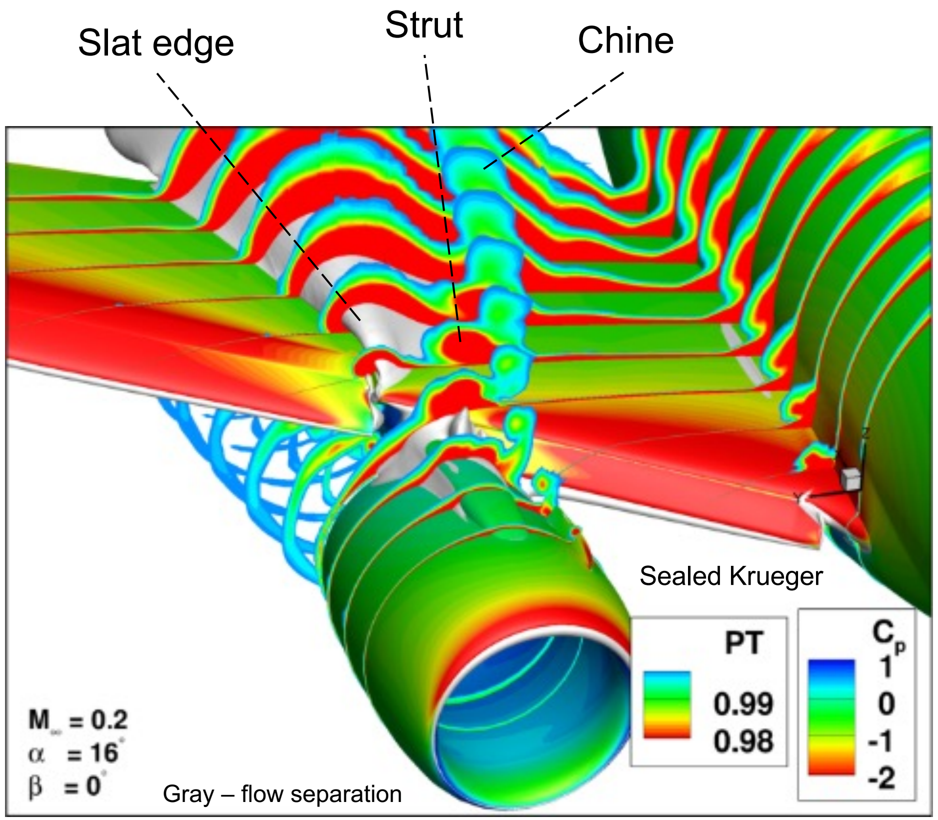
Baseline



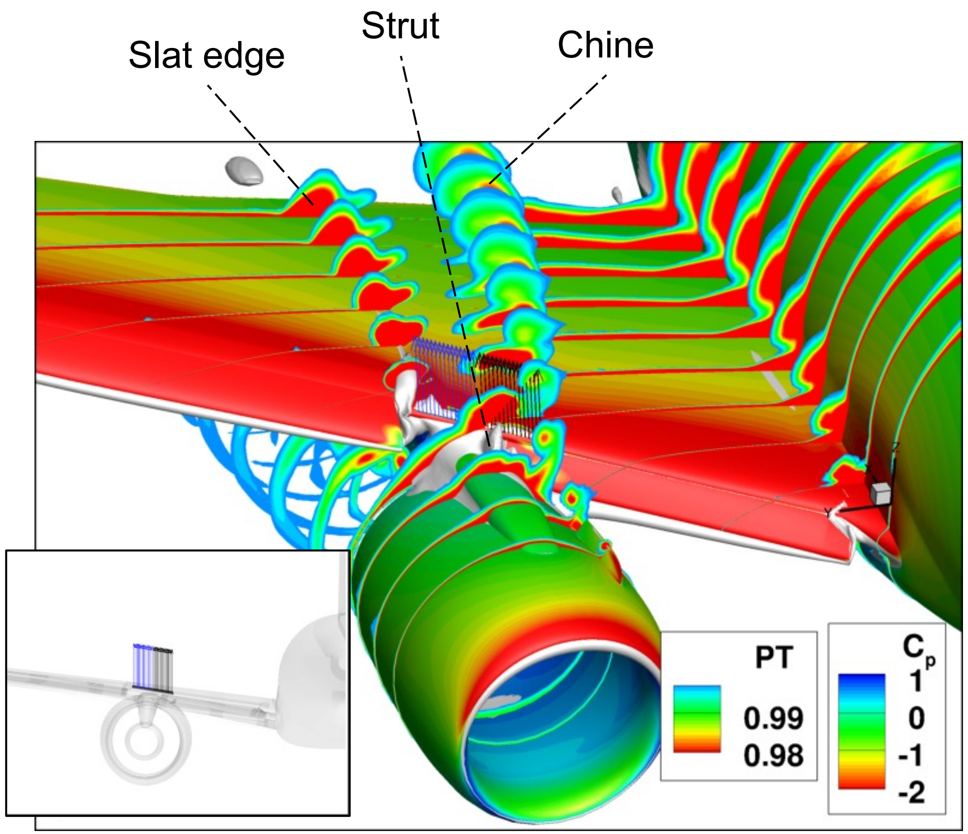
AFC
On the wing, on the IB and OB sides of the pylon

Nacelle/Pylon/Wing at α=16°

AFC helps reduce separation from slat edge and strut



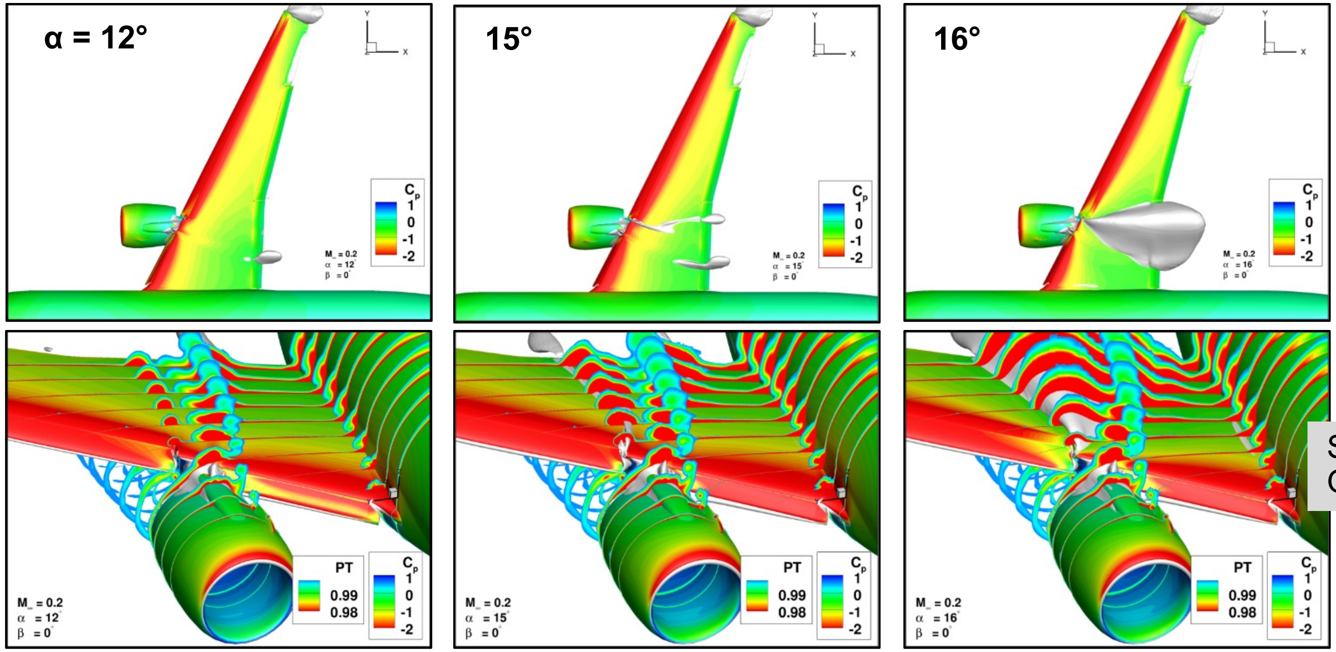
Baseline



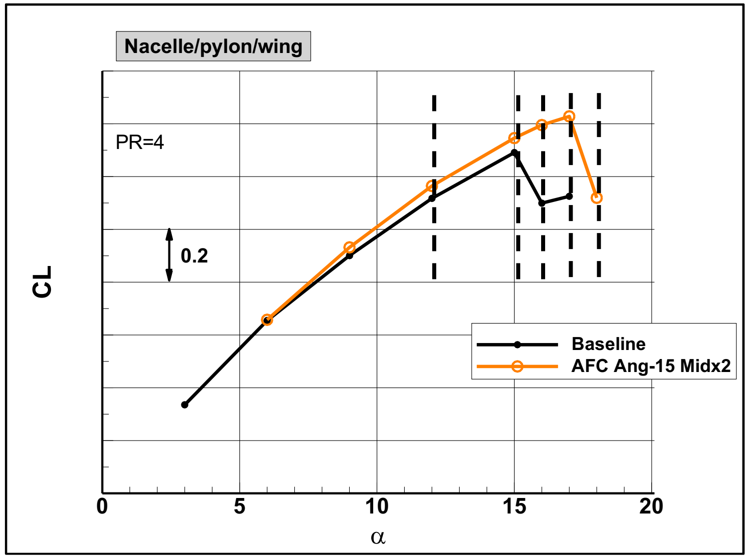
AFC
On the wing on the IB and OB sides of the pylon

Nacelle/Pylon/Wing – α Sweep

Baseline

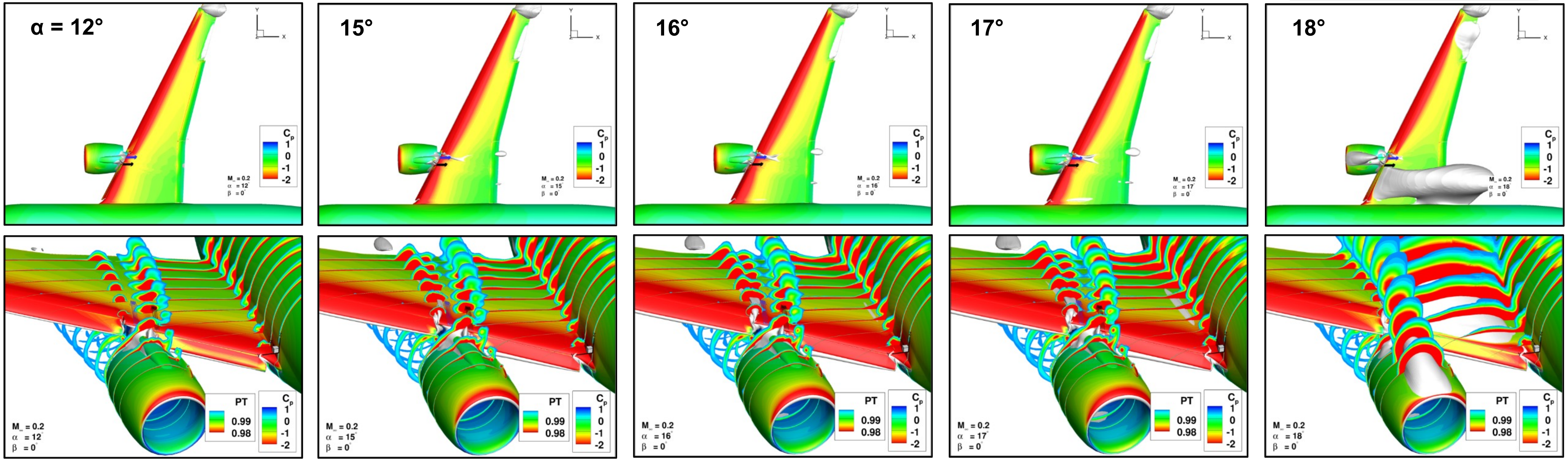


Sep triggered at OB side of pylon



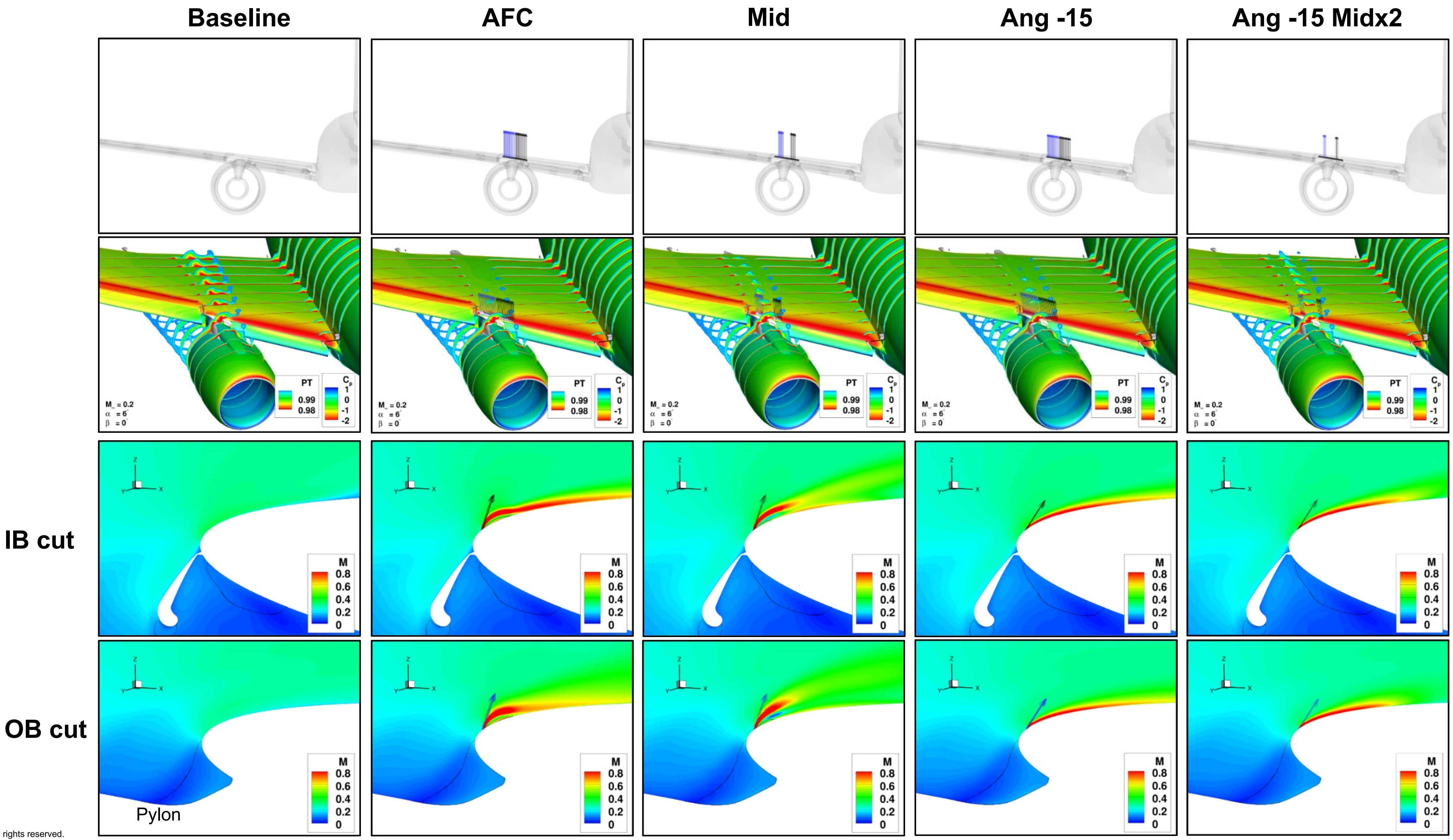
Sep triggered on the wing IB and at nacelle

AFC
Ang -15 Midx2



Nacelle/Pylon/Wing – AFC Patterns (α=6°)

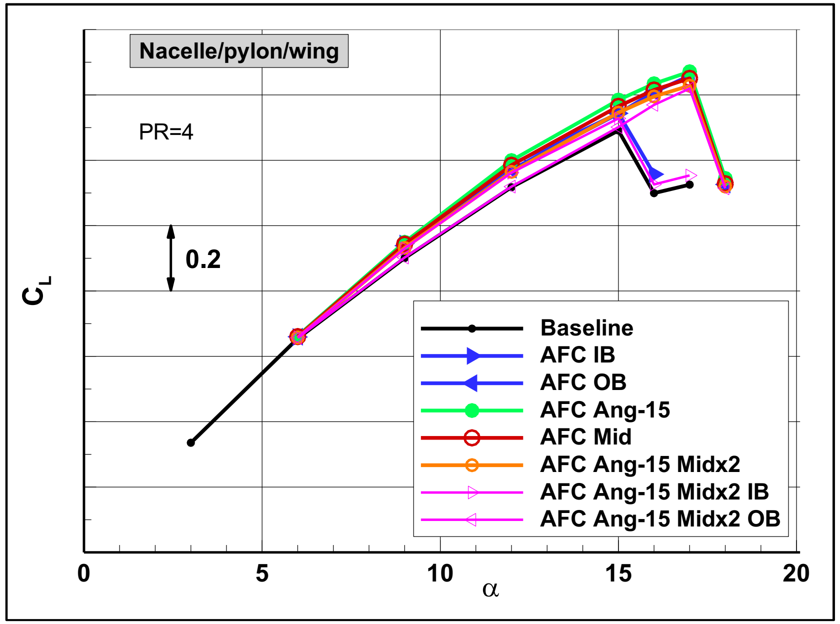
Jet size and orientation



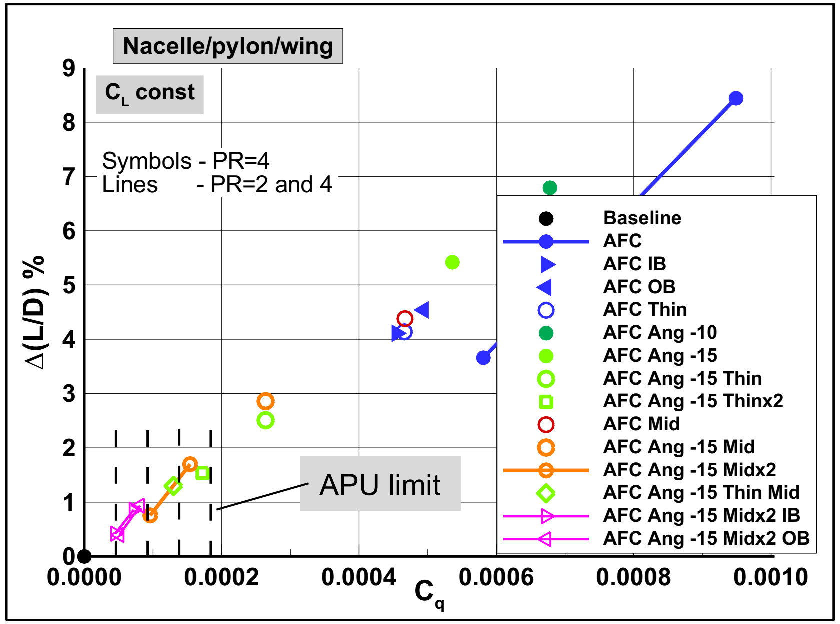
Nacelle/Pylon/Wing – AFC Patterns

Shallow jet angle is effective
OB actuation much more effective (takeoff setting)

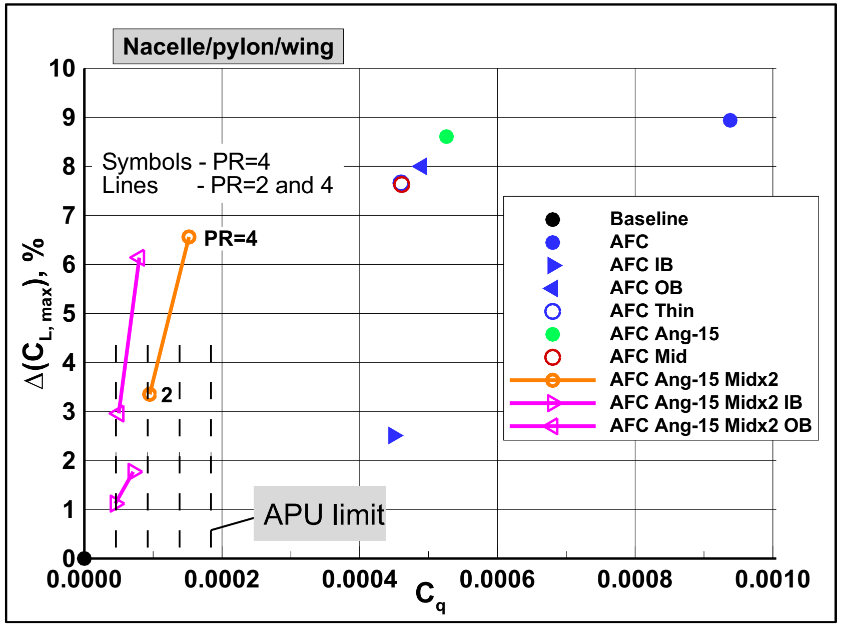
Lift curve



L/D at nominal takeoff



$C_{L\ max}$



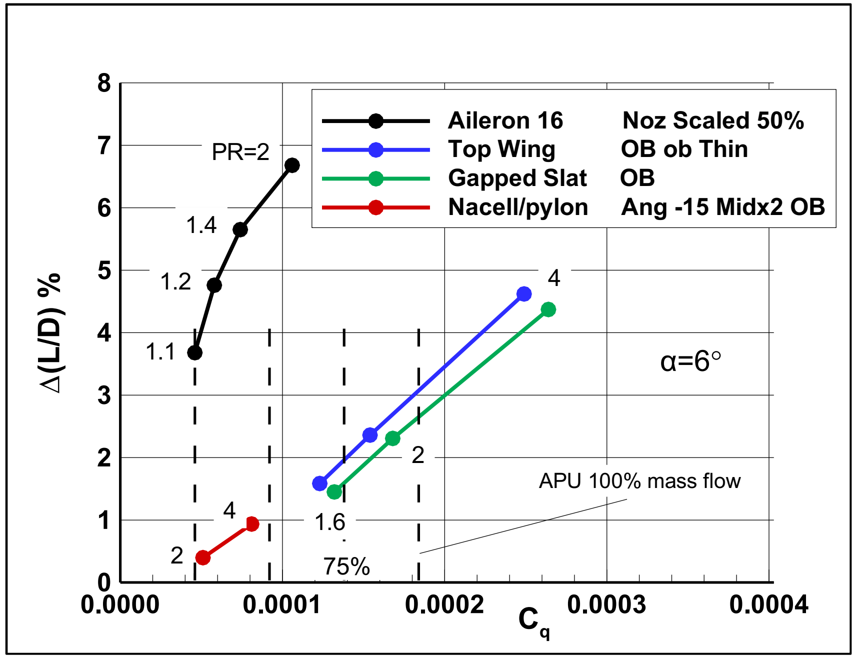
$\Delta L/D \approx$ 1-1.5%
$\Delta C_{L,max} \approx$ 6%

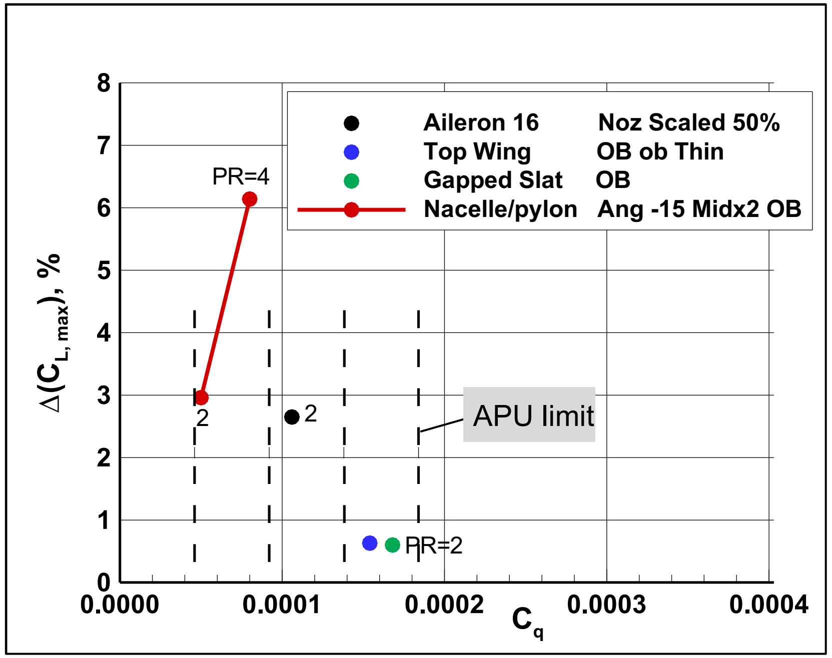
Baseline includes nacelle chine

Conclusions – Aileron & Wing LE

- Takeoff gains in CFD-predicted L/D of up to ~6% and $C_{L,max}$ up to ~6% can be achieved with onboard sources, depending on the application (aileron or LE)

Summary of AFC opportunities for the Aileron-16° and LE applications





- System integration study conducted to identify promising candidates

Dreaming
Collaborating
Innovating
Exploring
Trailblazing

Conceptual Integration Studies of Localized Active Flow Control on the Wing of a Commercial Aircraft

Paul Vijgen[1], Alex Ziebart[2], Arvin Shmilovich[3], Rene Woszidlo[3]

[1] Boeing Commercial Aircraft (Retired)
[2] Boeing Commercial Aircraft
[3] Boeing Research and Technology

SCITECH2023
AIAA-2023-0657
Session: APA-24, Flow Control Applications
Including Experiment and Computation IV
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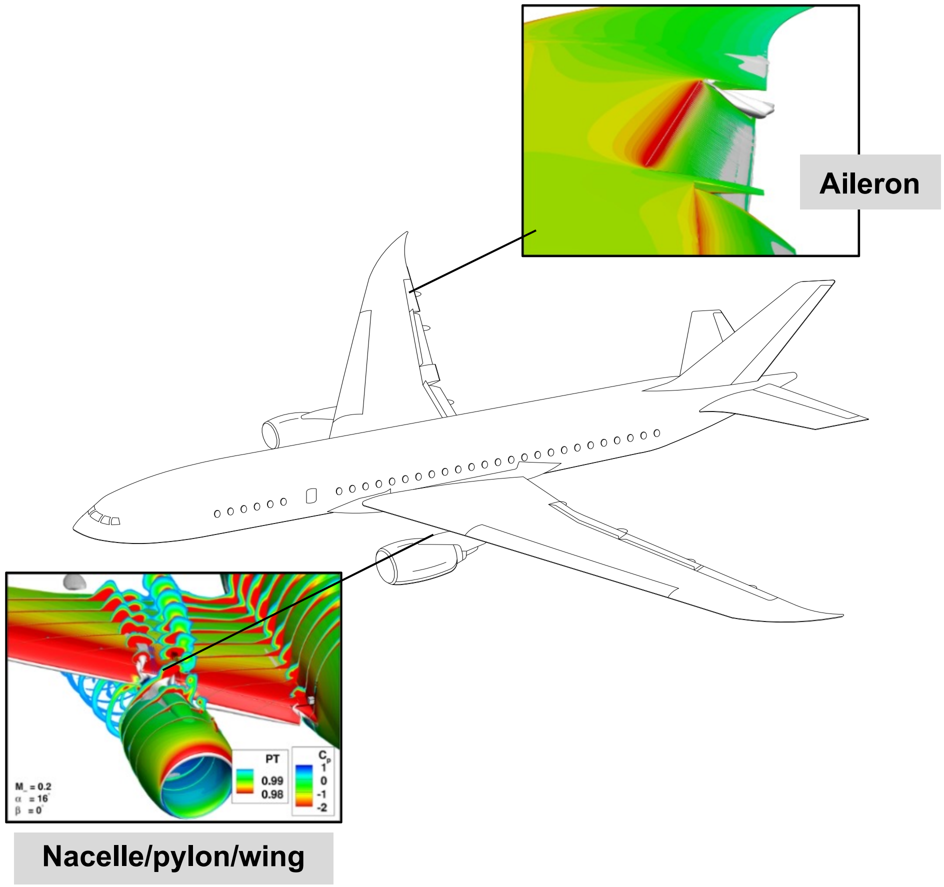
Producing
Leading
Creating
Researching
Analyzing

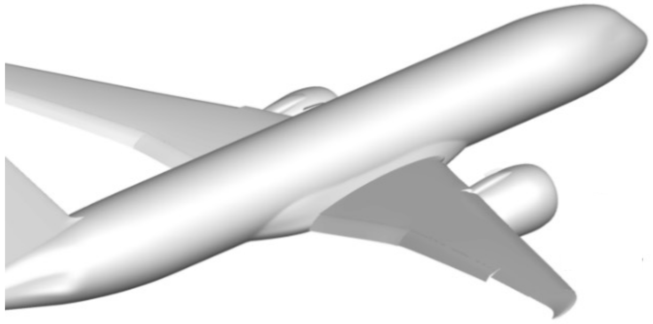
Conceptual Integration Study

- **Motivation**
  - Conduct airplane level Systems integration studies to assess potentially promising wing local AFC applications
- **Key steps**
  - AFC net aerodynamic benefits and structural penalties
  - AFC energy sources, Systems layout and weight
  - Estimated AFC net performance opportunities
- **Summary and next steps**

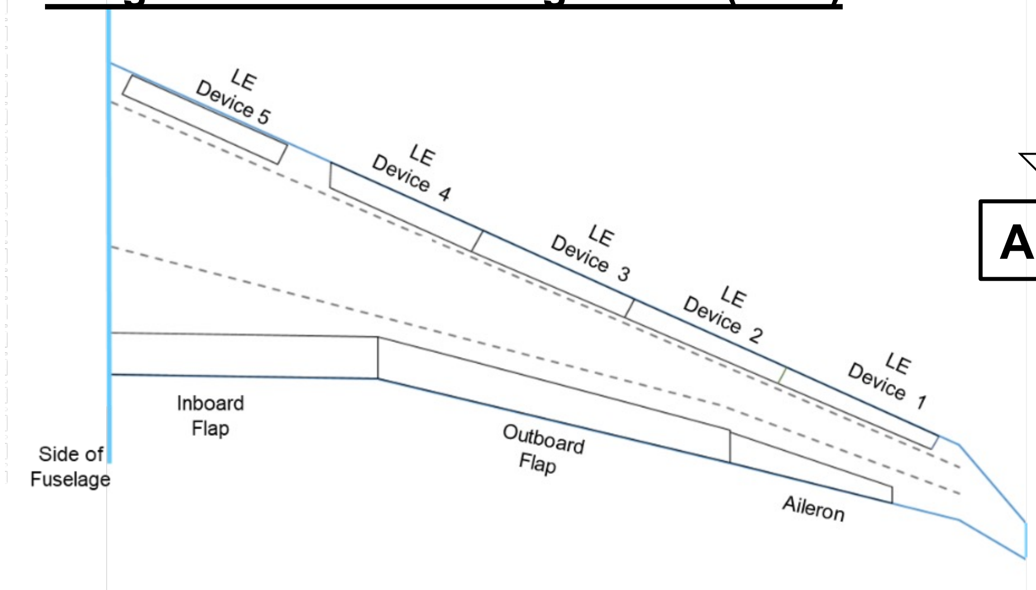


Configurations and Analysis Process

CFD Analysis Configuration (CRA)



Wing Performance Configuration (PRA)



CRA = CFD Reference Aircraft
PRA = Performance Reference Aircraft

CFD Aero AFC Increments (CRA) ← HLCAT, Aero-Elastics → **Aero AFC Increments (PRA)**

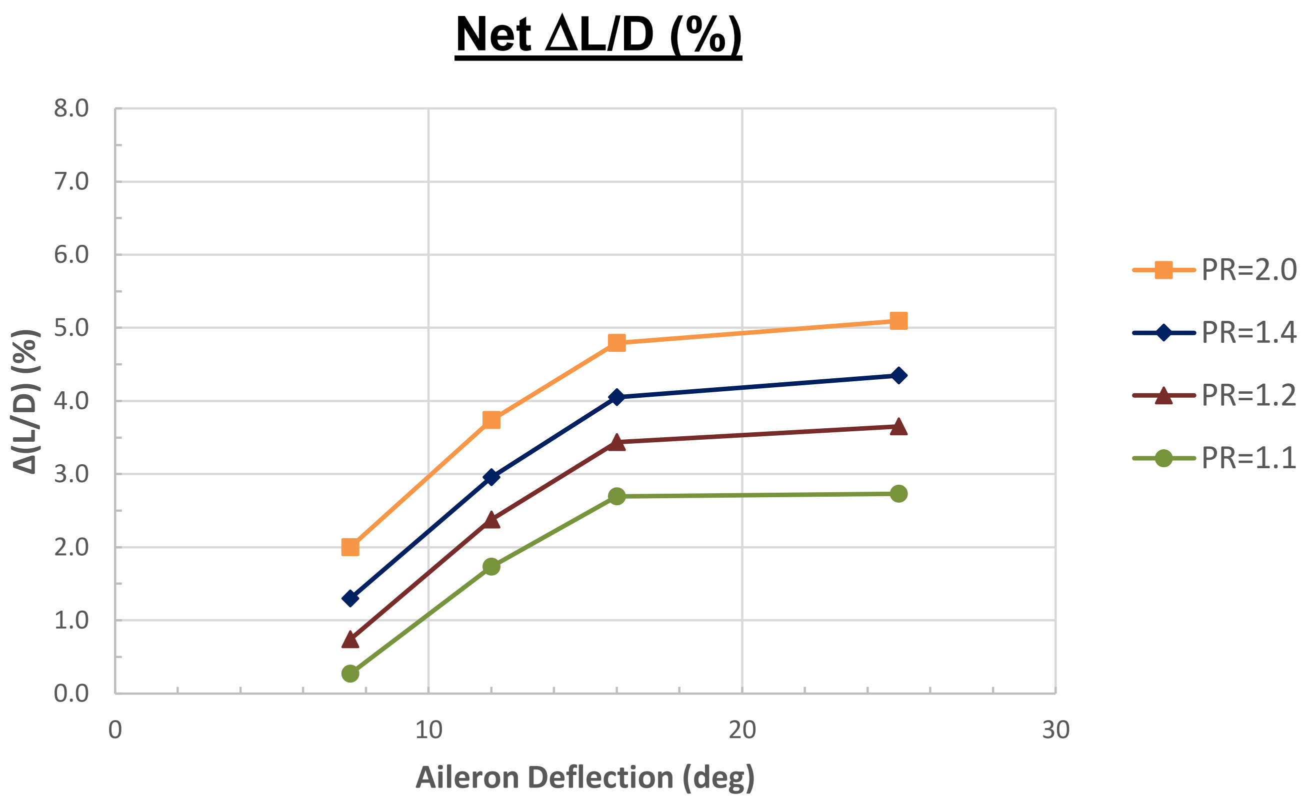
CFD AFC Energy Requirements (CRA) → **AFC Energy Requirements (PRA)**

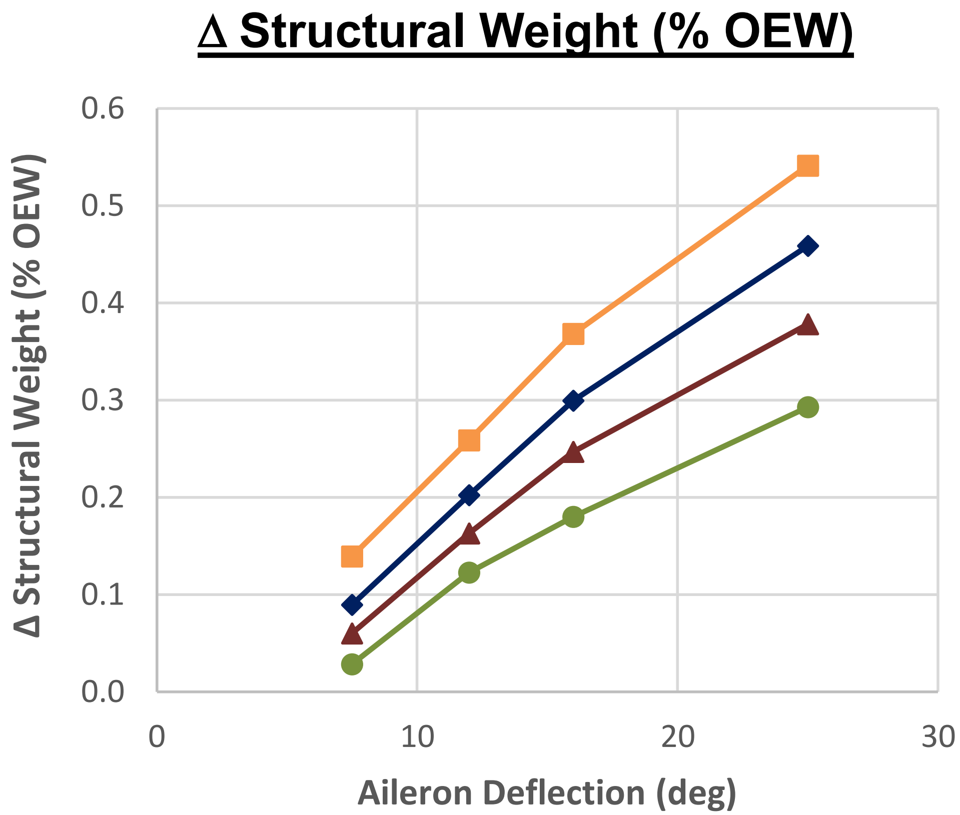
Aero AFC Increments (PRA) ← Structural Weight Increments with AFC, AFC Systems Weights Increment, AFC cruise drag/Fuel Burn Increment → **AFC Net Performance Opportunities (PRA)**

Performance Trade Factors PRA → **AFC Net Performance Opportunities (PRA)**

- Focused on applications with Takeoff flap setting
- Translated increments to non-rigid PRA configuration
- Identified on-board Systems/integration options for AFC
- Assessed conceptual net performance opportunities

Aileron – Aerodynamic and Structural Increments (Takeoff)

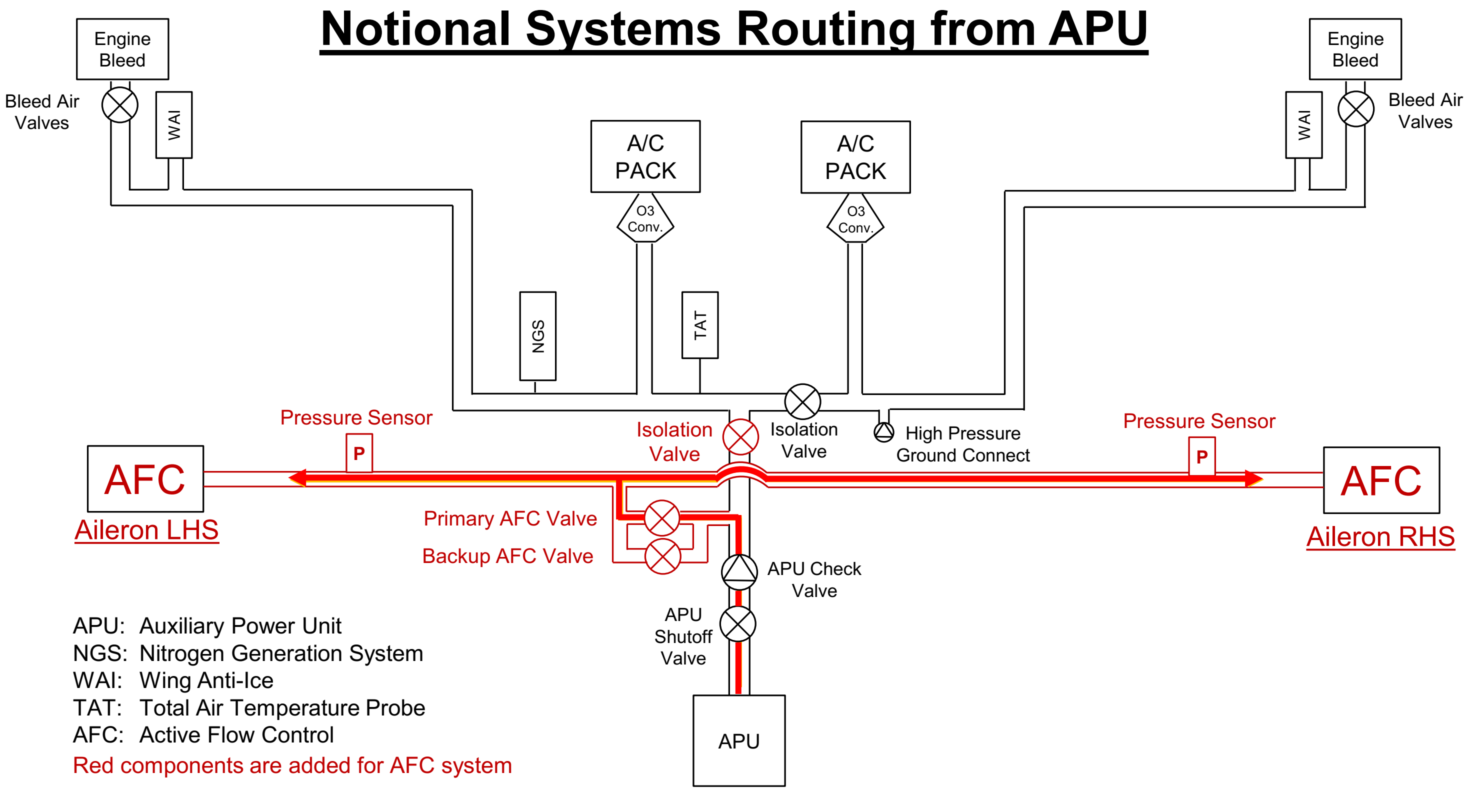


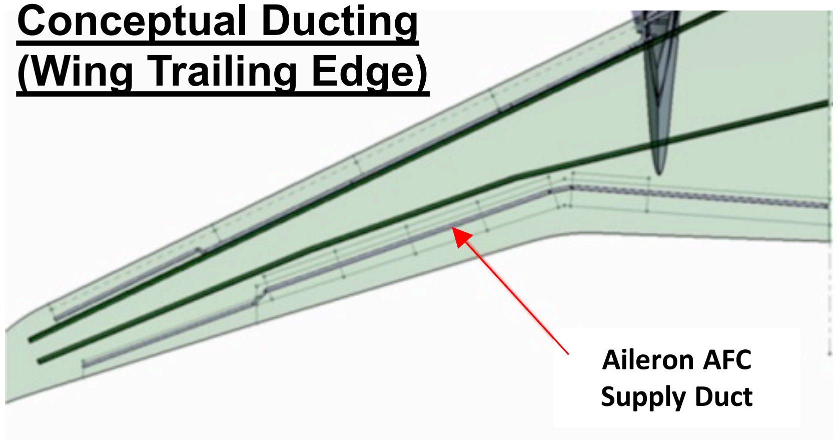


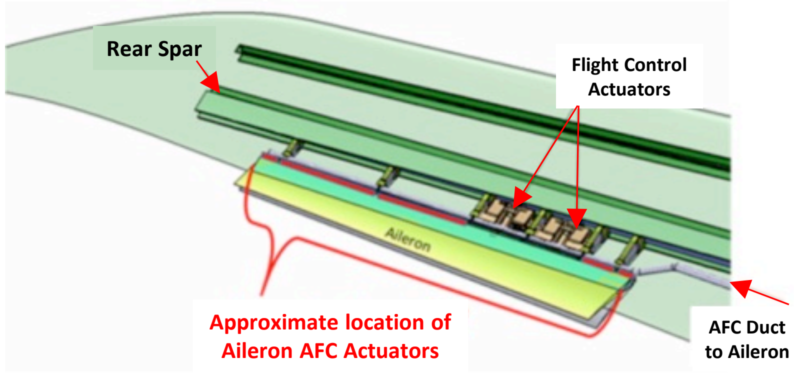
- L/D increments adjusted for CRA-to-PRA geometry and for PRA aero-elastic, trim, and thrust effects
- PRA wing structural weight penalty 0.2 – 0.4% OEW (due to increased outboard loading)
- PRA net L/D improvement **3 – 5%** with aileron deflections of 12° – 16°

PR = AFC Actuator Pressure Ratio

Aileron – APU Powered Systems





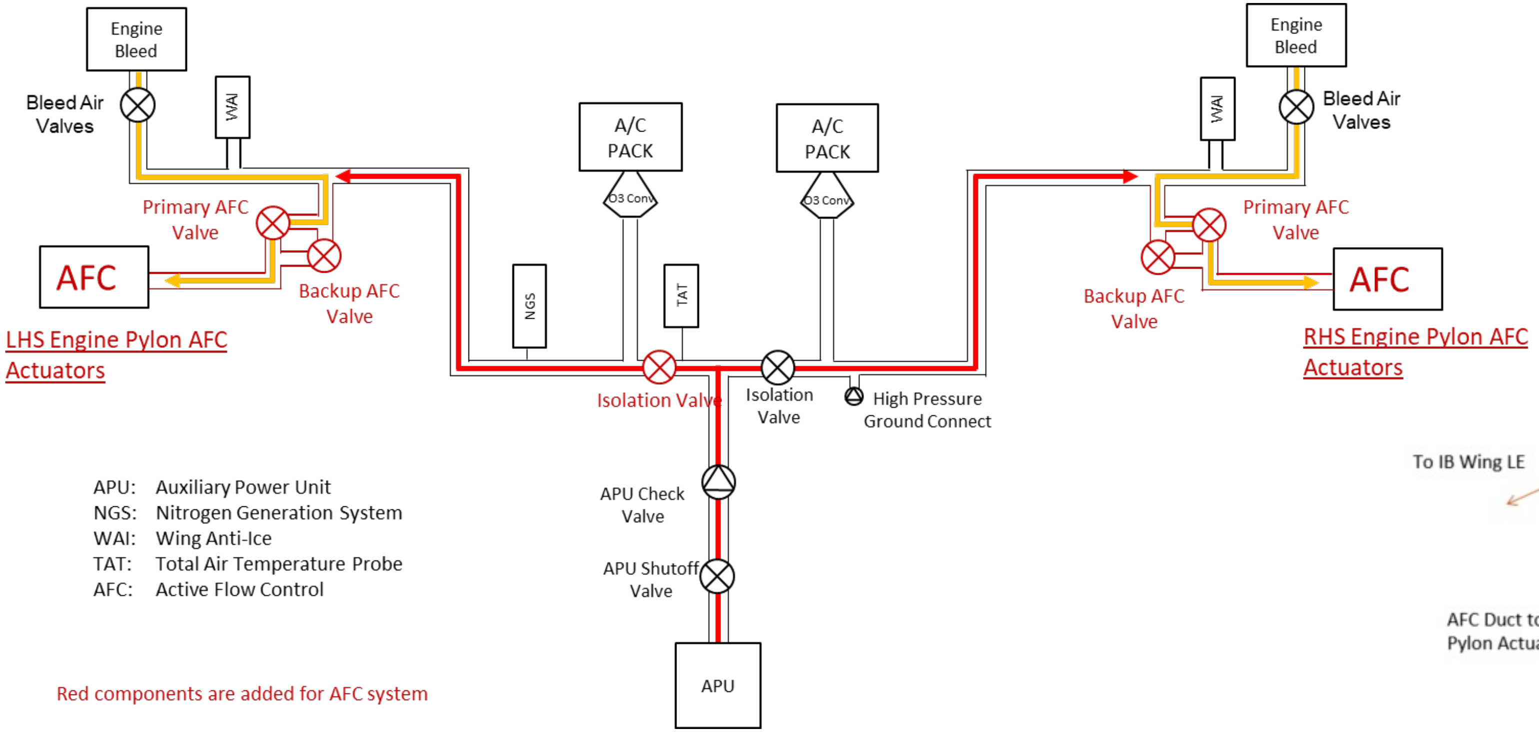


- APU load compressor can likely supply AFC energy (mdot and PR)
- Operation of APU during low-speed flight affects APU cost and maintenance
- Utilize existing ducting from APU to fuselage A/C Packs
- APU availability/reliability appears adequate - further study needed (detailed FHA)
- Integrating AFC duct in wing trailing edge is possible (but challenging for smaller aircraft)
- AFC Systems' weight increments included in performance study

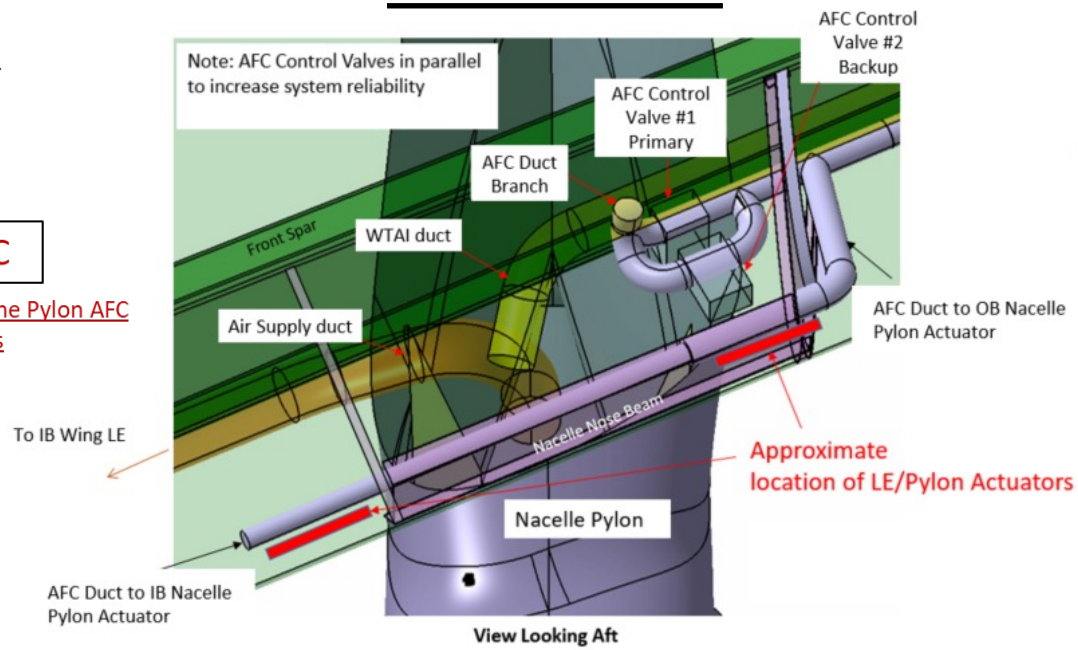
A/C = Air Conditioning
FHA = Fault Hazard Analysis

Nacelle/Pylon/Wing – APU/Bleed Powered Systems

Notional Systems Routing from APU/Bleed



Ducting to Nacelle/Pylon/Wing AFC Actuators



- APU and engine bleed share common duct (minimal additional ducting and weight)
- APU is primary AFC flow source in Takeoff; engine bleed is primary AFC source in Landing
  - APU provides backup AFC source to engine bleed (and vice versa)
- Systems availability/reliability appears adequate - further study needed (detailed FHA)
  - Balancing bleed demands for all pneumatic systems (WAI, EAI, A/C Packs, AFC)

FHA = Fault Hazard Analysis
WAI = Wing Anti-Ice System
EAI = Engine Anti-Ice System

Assessing Aircraft Performance Opportunities

Two Performance Scenarios Studied

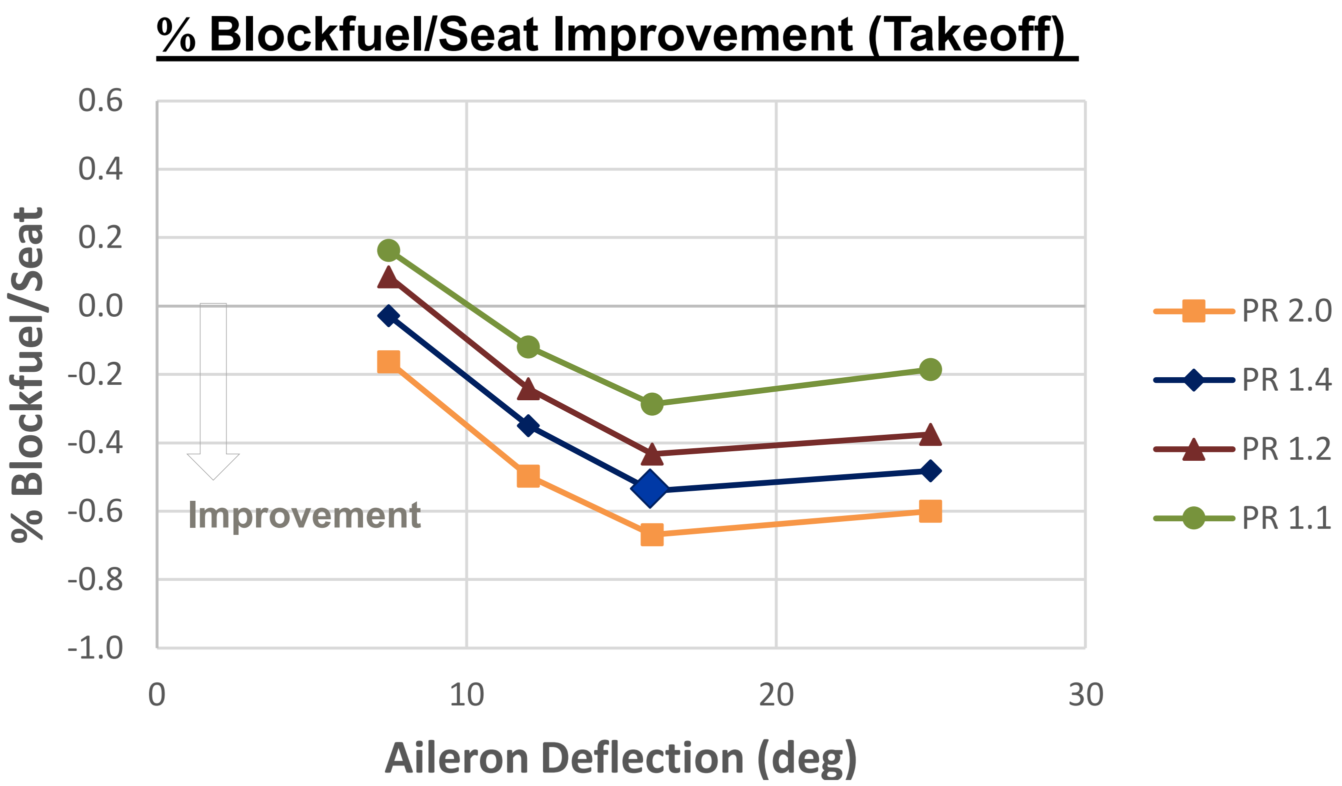
1. **AFC <u>affects</u> Aircraft Sizing**

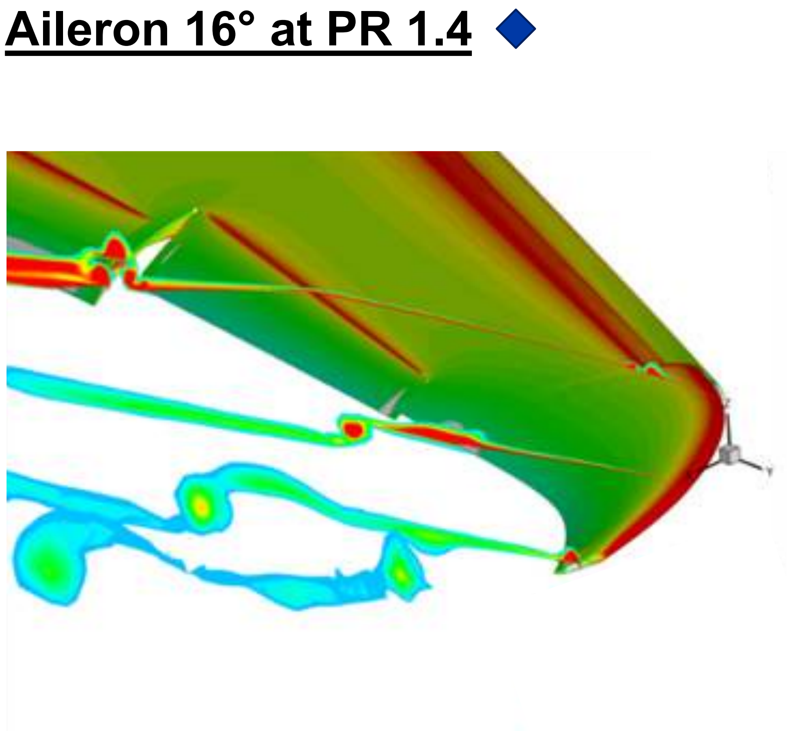
   – Wing Area, Engine Thrust, OEW, flap area, fuselage Takeoff attitude (incl. family stretch strategy)
   – In Takeoff: L/D critical for Hi-Hot Takeoff sizing constraint → Fuelburn/seat opportunity
   – In Landing: $C_{L,max}/C_{L,app}$ critical for V_{app} → Affects wing size/flap size → Fuelburn/seat opportunity

2. **AFC does not affect Aircraft Sizing**

   – AFC can benefit airline operations (life-cycle airline value) to mitigate Hi-Hot Takeoff constraints
   – Hi-Hot Takeoff payload increase and Engine Derate → airline operating cost opportunity

Sizing Scenario / Net Airplane Benefit - Aileron



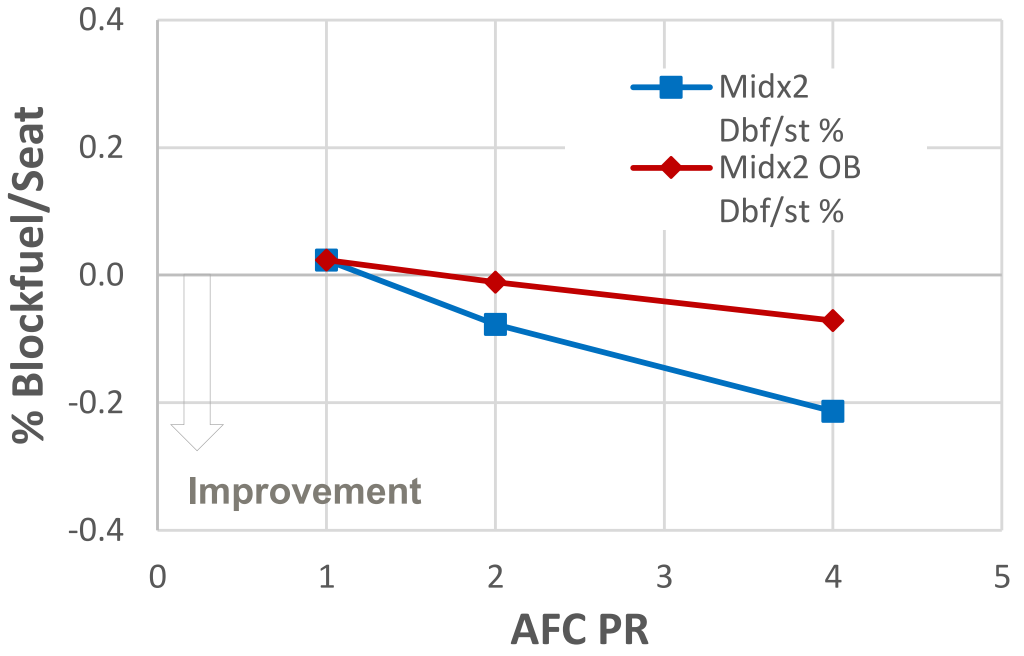


- Takeoff L/D is a key parameter that can affect sizing of wing area and engine thrust (Hi-Hot Takeoff)
- AFC related structural and Systems weight increments, and APU inlet & AFC actuator drag, are included
- APU-powered AFC could provide net **0.4 – 0.6%** blockfuel/seat improvement (relative to non-AFC baseline)

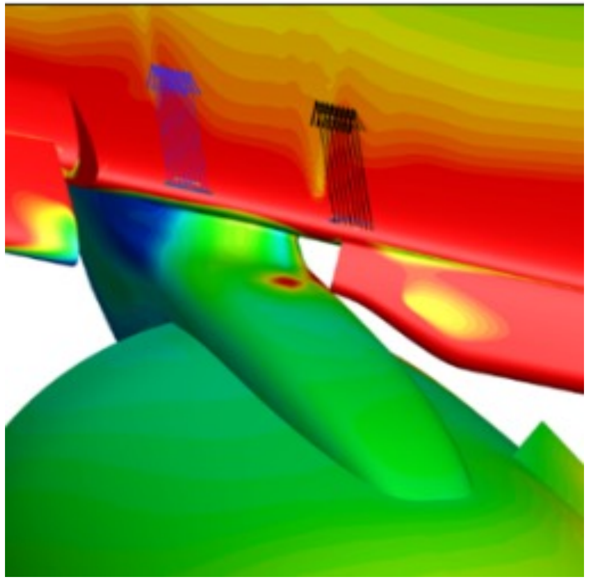
PR = AFC Actuator Pressure Ratio

Sizing Scenario / Net Airplane Benefit – Nacelle/Pylon/Wing

% Blockfuel/Seat Improvement (Takeoff)



Midx2 AFC Actuation



- AFC concept studied provides L/D benefit in Takeoff (with PR 2 – 4)
- AFC related Structural and Systems weight increments, and APU inlet & AFC actuator drag, are included
- APU-powered AFC could provide net **0.1 – 0.2%** blockfuel/seat improvement (relative to non-AFC baseline)
- Study did not address nacelle/pylon/wing AFC in Landing - potentially larger benefits (impact on $C_{L_{max}}$)

PR = AFC Actuator Pressure Ratio

Assessing Aircraft Performance Opportunities

Two Performance Scenarios Studied

1. **AFC affects Aircraft Sizing**

   – Wing Area, Engine Thrust, OEW, flap area, fuselage Takeoff attitude (incl. family stretch strategy)
   – In Takeoff: L/D critical for Hi-Hot Takeoff sizing constraint → Fuelburn/seat opportunity
   – In Landing: $C_{L,max}/C_{L,app}$ critical for V_{app} → Affects wing size/flap size → Fuelburn/seat opportunity

2. **AFC <u>does not affect</u> Aircraft Sizing**

   – AFC can benefit airline operations (life-cycle airline value) to mitigate Hi-Hot Takeoff constraints
   – Hi-Hot Takeoff payload increase and Engine Derate → airline operating cost opportunity

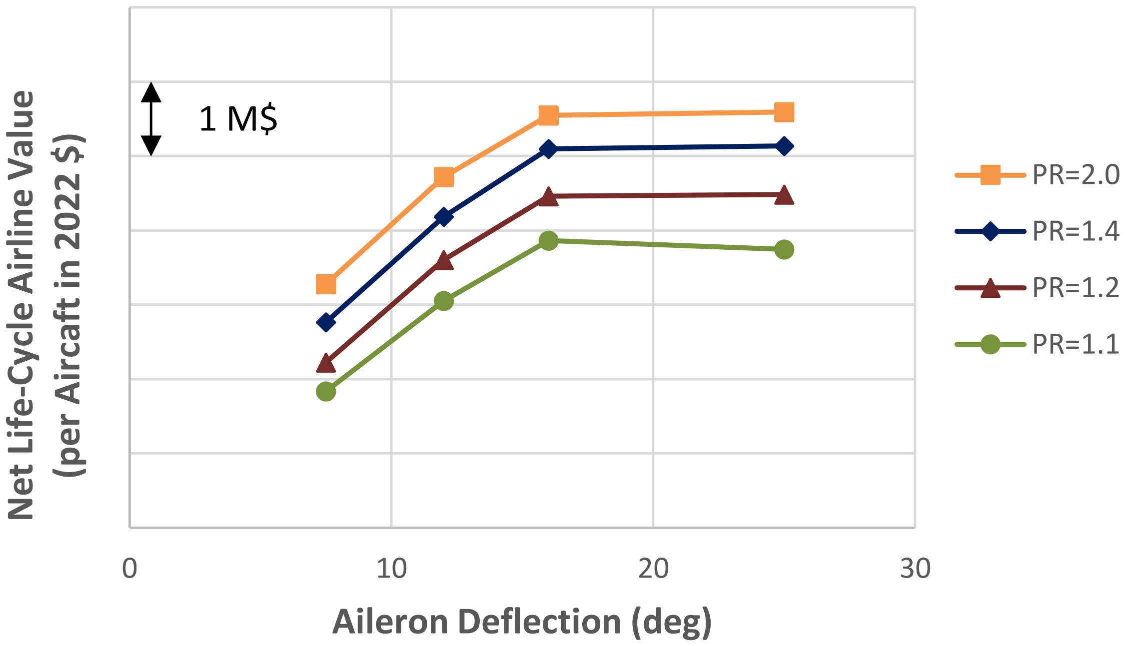
Non-Sizing Performance Scenario - Aileron

- **AFC Operational Opportunities**
  - More passengers (payload) for gradient-limited Hi-Hot Takeoffs
  - Reduced engine thrust setting (derating) for *non*-gradient-limited Takeoffs
- **Life-Cycle Analysis with Takeoff L/D Increase**
  - AFC Systems, wing structural weight penalty and APU operations translate into fuel burn increase
  - L/D increase offers potential net **5 – 8% increase** in payload for gradient-limited Takeoffs
  - Assumed 25% of Takeoffs are gradient limited; non-gradient limited Takeoffs benefit from engine derating
  - Estimate net Life-Cycle Revenue Benefit is **several $M's per aircraft**

AFC Operational Opportunities

Aileron droop (deg)	Net payload increase (gradient limited airports)	Block fuel change (economical mission)	Engine takeoff thrust derate (nongradient limited airports)
7.5	1.9%	+ 0.12%	0.8%
12	5.6%	+ 0.18%	2.0%
16	8.0%	+ 0.23%	2.9%
25	8.3%	+ 0.32%	3.1%

Life-Cycle Revenue Benefit



Summary and Next Steps

Summary

- **CFD was used to explore AFC opportunities and requirements**
- **Conceptual study indicates wing AFC integration is feasible with relevant aircraft net performance benefits**
- **Study resources mostly focused on aileron AFC, but found encouraging results for LE application**

Next steps

- **Validation of CFD results**
  - CRM-HL with aileron AFC tested at NASA-LaRC 14x22-ft tunnel (Feb-March 2023)
- **Further studies on wing AFC integration and performance opportunities**
  - FHA for studied AFC energy sources (APU, Bleed, other)
  - Detailed performance/sizing for Takeoff and Landing scenarios
  - Further CFD and integration definition of LE applications (UHBR nacelle junction and slat/wing tip)
  - Detailed Systems design and validation of integrated AFC hardware (ground and flight testing)

LE = Leading Edge
FHA = Fault Hazard Analysis
UHBR = Ultra High Bypass Ratio

References

NASA Reports

1. Woszidlo, R., Shmilovich, A., and Vijgen, P., "Low-Speed Performance Enhancement using Localized Active Flow Control – Program **Overview** and Summary", *NASA Technical Reports Server*, April, 2022, document ID: 20220006728.
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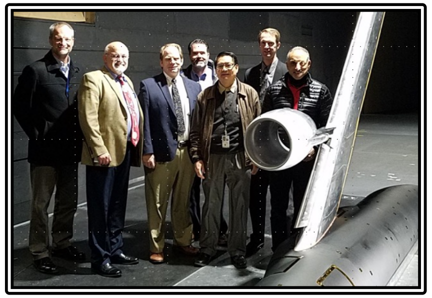
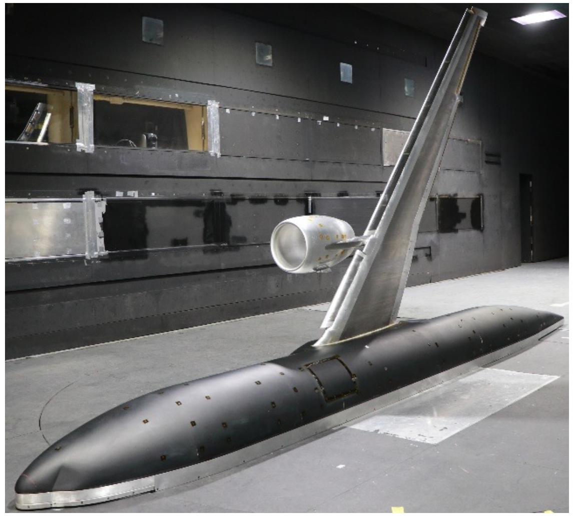
AIAA papers

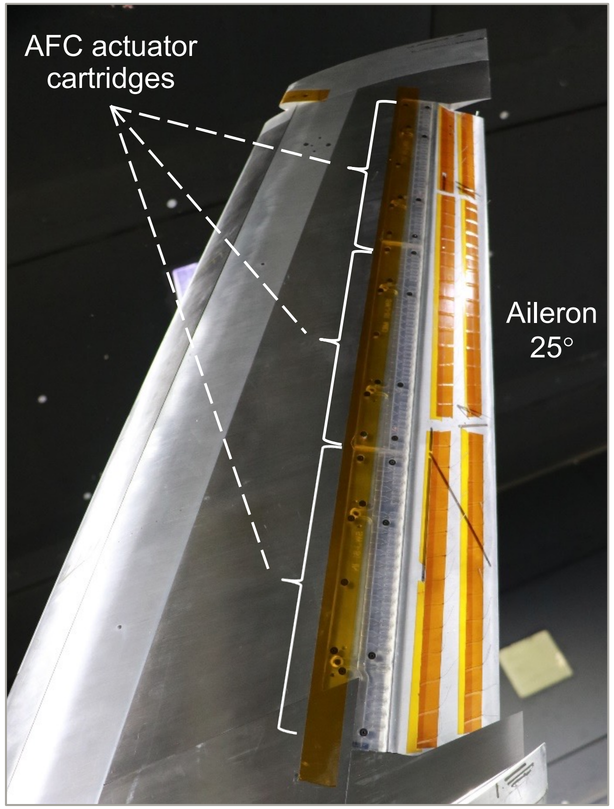
1. Shmilovich, A., Yadlin, Y., Vijgen, P., & Woszidlo, R., "Flow Control for Enhanced **Aileron** Effectiveness on a Commercial Aircraft," AIAA Paper 2023-0655, SciTech2023, 10.2514/6.2023-0655.
2. Shmilovich, A., Yadlin, Y., Vijgen, P., & Woszidlo, R., "Applications of Flow Control to Wing High-Lift **Leading Edge** Devices on a Commercial Aircraft," AIAA Paper 2023-0656, SciTech2023, 10.2514/6.2023-0656.
3. Vijgen, P., Ziebart, A., Shmilovich, A., and Woszidlo, R., "Conceptual **Integration** Studies of Localized Active Flow Control on the Wing of a Commercial Aircraft," AIAA Paper 2023-0657, SciTech2023,10.2514/6.2023-0657).

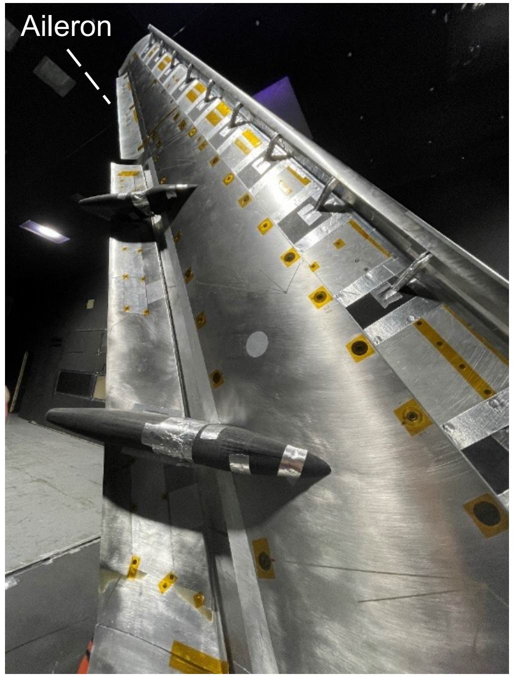
NASA Wind-Tunnel Model of the AFC-Enhanced Aileron

- **NASA Langley 14x22**
  - CRM-HL aileron AFC test
  - 10% scale model
  - Test conducted Feb-March, 2023









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